AD NUMBER

052 145

LIMITATION CHANGES

TO

Approved for Public Release;
Distribution Unlimited...
... Code: A/1

FROM

Distribution Authorized to U.S.
Gov't Agencies and their Contractors...

Code: C/2

AUTHORITY

Chief of Naval Research, via Ltr., dtd 22 Oct 93,
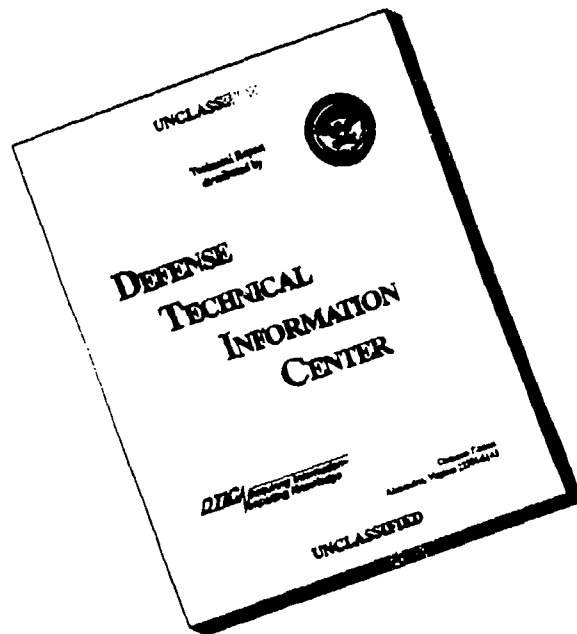Ser 931/1349, 5510/1

UNCLASSIFIED

AD_ 52.145

UNCLASSIFIED

DISCLAIMER NOTICE

THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

Second ONR SYMPOSIUM on DETONATION

February 9 and 10, 1955
NATIONAL ACADEMY OF SCIENCES
Washington, D. C.

February 11, 1955
U. S. NAVAL ORDNANCE LABORATORY
White Oak, Maryland

This document has been reviewed in accordance with
OPNAVINST 5510.17, paragraph 5. The security
classification assigned hereto is correct.

Date: 4/12/55

By direction of
Chief of Naval Research (Code 425)

55AA 1858

FOREWORD

These papers are to be presented at the Second Symposium on Detonation being sponsored by this Office on 9, 10, and 11 February 1955. Two volumes are being issued, one containing the unclassified and the other the classified papers. Inasmuch as these preprints are receiving a limited distribution they are not to be considered as a substitute for publication in appropriate scientific journals.

The object of this symposium is to bring together scientists from government, university and industry to discuss recent advances in theory, experiment and application in this field of chemical physics.

This Office is of the opinion that the symposium at which these papers will be discussed will stimulate new research in this complex field. The relationship of advances in the knowledge of detonation phenomena to the effectiveness of the use of molecular explosives makes this aspect of science of importance to the Department of the Navy and the Department of Defense.

To all those who are contributing papers and plan to attend this symposium, the Office of Naval Research expresses its appreciation.

F. R. FIRTH
Rear Admiral, USN
Chief of Naval Research

ii

CONTENTS

FACTORS AFFECTING THE TRANSMISSION OF DETONATION
BETWEEN SMALL EXPLOSIVE CHARGES   1

A.D. Hampton, J. Savitt, L.S. Starr, R.H. Stresau
U.S. Naval Ordnance Laboratory
Silver Spring, Maryland

Introduction

Almost all intentionally established explosive reactions,
whether for laboratory experiments, commercial applications, or in
ordnance items, are initiated by means of relatively weak impulses.
These weak impulses, whether mechanical, electrical, or thermal,
generally ignite deflagration of the explosive material which, under
favorable circumstances, accelerates rapidly, generating shock waves
which may be intense enough to establish detonation. By the nature
of this process, the incipient detonation thus established is the
mildest reaction which can propagate as a detonation and must grow
to its stable rate. The various phases of this process have been
discussed by Kistiakowski[1], Bowden and Yoffe[2], Eyring et al[3]
Andreev[4], Gamow and Finklestein[5], and many others.

The use of a large charge of an explosive in which this entire
process will readily take place is so hazardous that it is almost
never done. The usual practice is that of subdividing the explosive
charge into two or more components in which there is a general
inverse relationship between size and sensitivity and of isolating
the smaller, more sensitive, components from the larger ones until
as shortly as possible before the charge is to be detonated.

Mechanical design considerations and the fact that the most
effective material for one phase of this process is not necessarily
the most effective for another phase results in further subdivision
of explosive charges. Practically every detonation of intentional
origin, in the course of its growth, has encountered one or more
discontinuities. The reliability with which detonation can be
transmitted across these discontinuities is affected by a wide
variety of factors including the properties of the explosive
materials involved, the densities at which they are loaded, the
materials in which they are confined, their absolute and relative

CONFIDENTIAL

sizes, their relative positions, and the nature and position of any
intervening materials. It is obvious that so many permutations of
these factors are possible that there will never be time to
investigate all of their interactions.

Most of the work which has been done by the authors in this
field has involved determinations of the conditions under which one
charge, which we have called the "donor", will initiate another
known as the "acceptor". In some cases, the donors and acceptors
were standard or proposed explosive train components such as
detonators, leads, boosters, or simulated main charges. More often,
special, idealized components have been used.

Experimentally, detonation is usually considered to have been
transmitted between two charges if the acceptor detonates with
nearly its maximum intensity. Under some circumstances the criterion
used to differentiate between "fires" and "misfires" introduces
questions of orders of detonation, but in most experiments the output
of the acceptor is either practically negligible or so near the
maximum that the differences are difficult to detect. It does not
follow that all charges classified as "fires" are initiated at their
stable detonation rates. The usual situation is quite the opposite
since in experiments aimed at determining the threshold conditions
for initiation, most trials will be made under conditions very near
the threshold. It does follow that most explosive charges, if they
detonate at all, build up to stable detonation quite quickly. The
transmission of detonation involves the completion by the donor of the
establishment of conditions which insure the growth of detonation.
Whether the dominant initiation mechanism is homogeneous compressive
heating of the solid explosive, interstitial heating related to
inhomogeneity, or ignition by air shock and reaction products,
conditions necessary for the growth of detonation are those of high
temperature and pressure.

In each of the transmission mechanisms mentioned, the growth of
detonation depends upon the rise of temperature and pressure due to
the excess of heat and gas evolved over that lost to the system. Due
to the short times involved in these processes, heat losses due to
conduction are probably second order effects so that the principal
cooling mechanism is the expansion of the gases and other materials
present. The most important factors which affect the transmission
of detonation are those which affect the vigor of the reaction which
is established in the acceptor and those which retard the expansion
of the products of the reaction. In most experimental situations,
the various factors involved are so interwoven that it is difficult
to separate their effects, but most of the experimental results
illustrate these generalities so obviously that this fact hardly
needs to be pointed out.

CONFIDENTIAL

CONFIDENTIAL

Experimental Procedure

General

The data discussed herein were obtained by a variety of experimental procedures. Quite a few of these experiments were determinations of the critical conditions for the initiation of detonation in one explosive element by means of another. The critical condition is defined as the least favorable of the series of related conditions for which the donor will initiate detonation of the acceptor. Such information unfortunately cannot be obtained for any one combination of a donor and an acceptor. All that can be learned from one shot is that the acceptor was or was not initiated. The first experiment which suggests itself is that of "working up" to the critical point from each side with a series of straddling shots using identical donors and acceptors. However, it is impractical, if not impossible, to make components which are nearly enough identical for this type of experiment, thus each set of donor and acceptor has a unique critical point. The experiment must be directed toward determining the average critical point which, upon a little reflection, can be seen to be the point at which 50% of the acceptors fire. During the past war a method for determining such statistics was devised by the Explosives Research Laboratory, Bruceton, Pa. It was analyzed and refined by the Statistical Research group of the Applied Mathematics Panel at Princeton. This method, which will be referred to herein as the Bruceton method, involves a series of trials the conditions for each of which are determined by the result of the previous trial, and is described in more detail in a report of the Statistical Research group of the Applied Mathematics Panel[6].

Criteria of Detonation

The Bruceton method is applicable only where the result of a single trial can be placed definitely in one of two categories; in the case of propagation tests, detonation or failure of the acceptor.

Detonation in a marginally initiated charge quite obviously is initiated at something less than its stable rate. Stable detonation is achieved only after a certain amount of the acceptor explosive has been consumed. As the vigor of initiation is increased, the quantity of explosive consumed in the growth process should be expected to decrease with a corresponding increase in the output of the acceptor as indicated by the damage to its case or by other criteria which might be used. Thus, in an experiment to determine the conditions under which detonation is transmitted from one charge to another, the result may depend upon the criterion of detonation used to classify a given trial as a "fire" or "misfire". The seriousness of this effect depends upon the relationship between the rate of build-up and the variation of characteristics from one individual donor or acceptor to another. It will be shown in a later section

Sumpton, Savitt, Star , Streasau

of this paper that this effect can be quite serious under some
conditions but that it has negligible influence in the range of
conditions under which most of the data reported herein were obtained.
In the Bruceton up and down experiments which were used to obtain a
large part of these data, individual trials in which the classifi-
cation would have been changed by a reasonable change in the
criterion of detonation were rare.

Physical Arrangement

Although data obtained by means of a variety of experiments are
discussed herein, experiments of the kind schematically illustrated
in Figures 1 and 2 are the sources of most of the data.
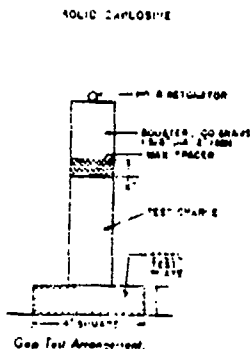
Figure 1
Booster Sensitivity Test[7]
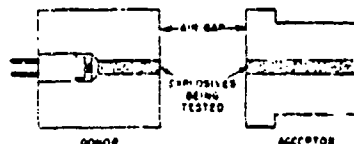
Figure 2
Small Scale Gap Test[7]

The experimental arrangement shown in Figure 1 was used by
Eyster, Smith, and Walton[8] to investigate the effect of a variety
of factors upon the transmission of detonation. That shown in
Figure 2 has been used extensively by the authors of this paper.
The energy transfer between donor and acceptor in the booster
sensitivity test is accomplished by the transmission of shock waves
through and between solid materials, a relatively simple process.
Transmission across an air gap as in Figure 2 is somewhat more
complicated since the air in a shock zone is extremely hot, the
order of 10,000°C[9], and is followed by a mass of product gases
whose particle velocity is close to the shock velocity and whose

CONFIDENTIAL

density is quite appreciable. Both the high temperature of the air and the high kinetic energy of the product gases may be more important factors in the transmission of detonation than the air shock as such. The confinement, which is necessary because of the small scale, adds further complexity. The differences between these two types of experiments are such that any points on which they agree must be of reasonably general applicability.

Observations and Discussion

Factors Related to Dimensions of Explosive Charges

It is self evident that the effectiveness of the transmission of detonation should increase with the size of the donor charge. With very small donors, the diameter effect can cause significant decrease in the stable detonation velocity and the detonation may not grow to its maximum stable rate. After stable detonation at a rate closely approximating the plane wave detonation rate has been achieved, the effectiveness of a donor continues to increase with size because the larger mass of explosive products takes longer to expand and thus maintains conditions conducive to growth of detonation in the acceptor for a longer time. In a gap or barrier test, this combines with the general scaling law which applies generally to explosion phenomena. As the diameter of the donor is increased the critical gap or barrier thickness increases more rapidly. In Table I some data of Eyster, Smith, and Walton[6] show this relationship.

Booster Diam.	Weight	Critical Thickness, Wax Barrier			
(inches)	(gm)	Pentolite	Comp A-3	Comp B	Picratol 52/48
1.00	40.8	1.13	0.93	0.73	0.41
1.57	100.	0.78	1.70	1.22	1.00
2.50	254.	3.50	3.91	2.29	1.7

Table I
Booster Sensitivity Test - Scaling Experiments
(Tetryl Booster - Two Inches Long)

The relationship is also apparent in Figure 3 from data on some of the present authors. The deviation from geometrical scaling can be ascribed to the time factors involved. The times associated with the hydrodynamic shock phenomena are essentially transit times and hence vary proportionally with linear dimensions while the reaction time of the acceptor explosive is dependent upon local conditions in the reaction zone.

The principal effect of acceptor diameter is that upon the resistance of the system to the expansion of the material of the

CONFIDENTIAL

reaction zone. When an explosive charge is unconfined, its
resistance to expansion increases, of course, with its diameter so
that larger charges are more easily initiated. This effect has been
demonstrated by Eyster, Smith, and Walton[8]. When the acceptor is
heavily confined in a metal such as copper, the effect of its
diameter upon its apparent sensitivity is somewhat more complex. The
explosive material affords less resistance to expansion than the
confining medium so that a small reaction nucleus is supported by the
proximity of the walls. Thus the apparent relative sensitivity of the
acceptor depends upon the donor diameter. Figure 3 shows this quite
forcibly. Note that, under the conditions of these experiments, the
optimum acceptor diameter is slightly less than the donor diameter.
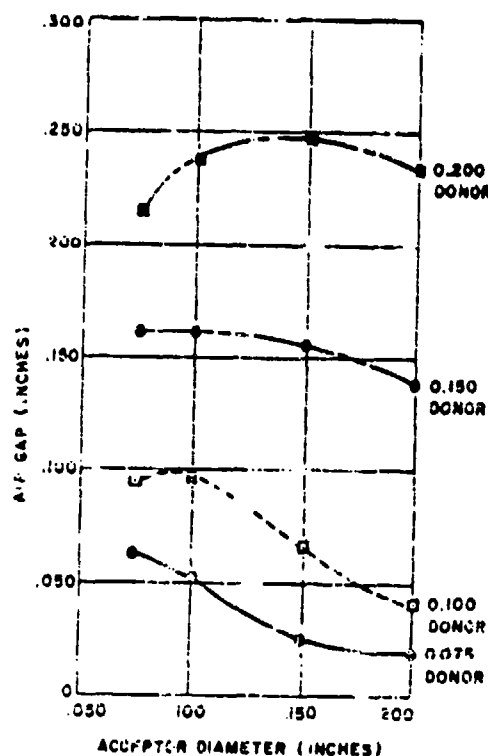
Figure 3
Air Gap in the Small Scale Gap Test as Related to Acceptor
and Donor Diameter

Where the growth of detonation is incomplete, the effectiveness
of a donor may be expected to increase sharply with length. This
principle is of great practical importance when the donor and
acceptor are the intermediate and base charge of a detonator. It is

6

CONFIDENTIAL

Hampton, Savitt, Starr, Streasu

discussed in some detail by the present authors in a recent
paper(10). Where the transition from burning to detonation takes
place in lead azide it is so rapid that the effect of column length
observed in most experiments is that associated with the growth of
the "head" of reaction products rather than that of the detonation.
As the length of a donor column is increased the length of the head
of gases behind the detonation front is increased up to the point
where radial losses become preponderant. Beyond this point, further
increases in length result in no increase in effectiveness. This
point depends upon the manner in which the donor is confined. The
length of the head affects gap test results through its effect on the
attenuation of the transmitted shock and accompanying phenomena and
in resisting the rearward expansion of the acceptor reaction products.
As might be expected, a given increase in charge weight is less
effective in increasing the effectiveness of a donor when it is added
by increasing the length than when the diameter is increased,
Figure 4.
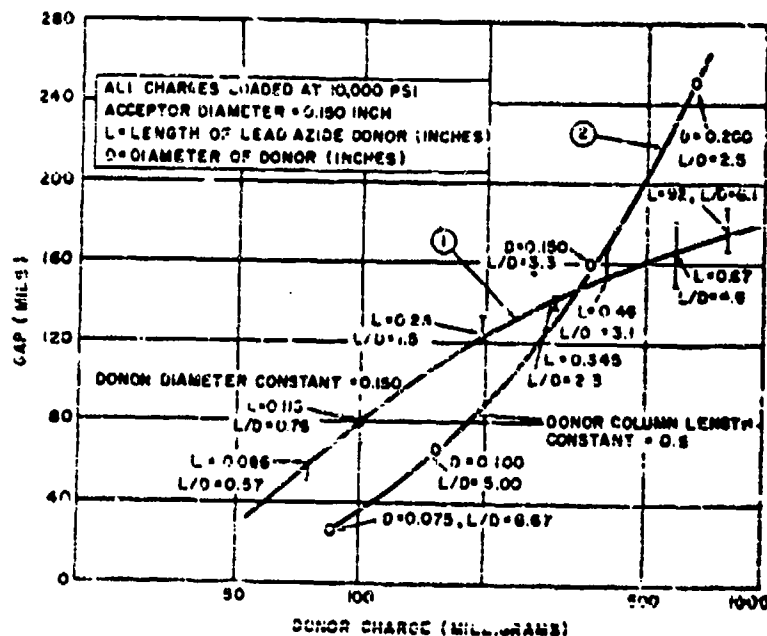
Figure 4
Critical Axial Air Gaps Across Which Detonation is
Transmitted Between Lead Azide and Tetryl

The effect of acceptor length upon the transmission of
detonation is usually quite small. Where a short donor is backed

7

by a metal plate, the shock reflected from the backing plate might be expected to reinforce the incident shock and increase the apparent sensitivity. One of the present authors has shown[11] that for one such system, the length of the donor had to be reduced to 0.025 inches, a very small fraction of any other dimension involved, before this effect could be detected. A second effect of acceptor length upon sensitivity which may be real or apparent depending upon interpretative point of view is that related to growth of detonation in the acceptor. Under circumstances where the growth of detonation may require a column length of the same order of magnitude as the acceptor, a longer acceptor might build up to a point where it would be classified as a "fire" while a similarly initiated acceptor of lesser length would be classified as a "misfire". In Figure 5 it is demonstrated that circumstances are possible under which appreciable column lengths are required for the growth of detonation.

x   1   2   3   4   6

Figure 5*

Explosive Container Fragments Showing the Effect of the Vigor of Initiation Upon the Growth of Detonation in Tetryl

*The distance (x) between a donor of PETN loaded at a pressure of 10,000 psi and the three inch long acceptor of tetryl, with a diameter of 0.300 inches, loaded at a pressure of 4,000 psi, was varied as indicated. Note that the growth to high order detonation in the acceptor as reflected by the distortion of the acceptor container can be quite gradual for large values of x and that the distance required in the tetryl for the reaction to grow to high order detonation increases with increasing x, that is with decreasing vigor of initiation.

Factors Related to Composition of Explosive

In general, explosives which are more "brizant" as indicated by high detonation velocity, large plate dent results, etc., are more effective as donors, and those which are more sensitive by other standards, such as impact sensitivity obtained using drop tests, are more sensitive acceptors. In experiments to determine the minimum booster required to initiate cast TNT it was found that 6.1 grams of RDX/wax, 97/3 is equivalent to 8.3 grams of tetryl. Figure 6 shows the correlation between impact sensitivity and critical air gap.
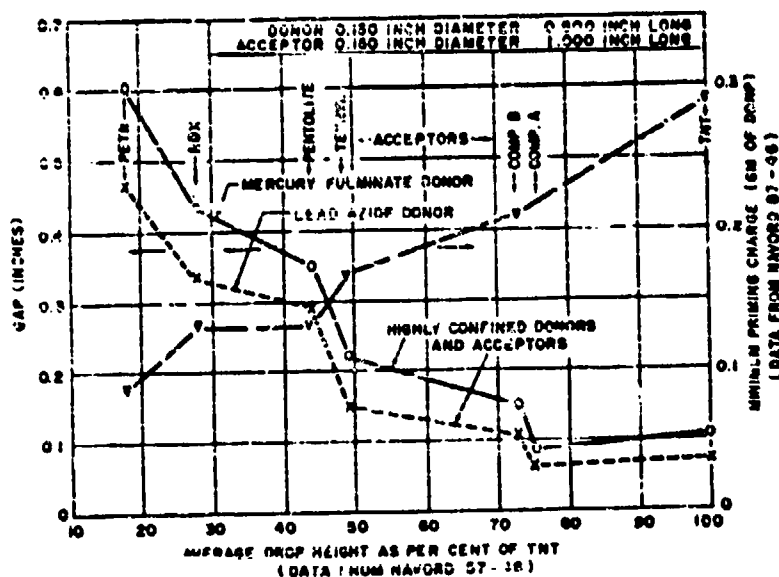
Figure 6

Minimum Priming Charge and Gap for Critical Propagation
as Related to Impact Sensitivity

Where the donor is very small, as for example in "minimum priming charge" experiments, the rapidity with which the explosive effects the transition from burning to detonation is the predominant factor in its effectiveness. Good correlation has been obtained between minimum priming charge experiments and other measurements of the rate of this transition[10].

The effect of additives upon sensitivity to initiation is not necessarily proportional to that upon impact sensitivity. The sensitivity of RDX to initiation by other explosives, for example, is much more sharply reduced by the addition of wax or similar materials than is its impact sensitivity. Note, in Figure 6, the inversion between Comp A and TNT.

9

CONFIDENTIAL

The correlation between impact and initiation sensitivity apparently does not apply to explosives which are mechanical mixtures of fuels and oxidizers. This may be related to the necessity for more intimate mixing during the reaction time. In some such mixtures considerable difficulty has been experienced in producing a material with acceptable impact sensitivity which can be initiated with a booster of reasonable size.

Factors Related to States of Aggregation

Charges of solid explosives are made either by casting them or by pressing from granular material. In either case large variations in grain or particle size are possible. In addition, the density of pressed granular explosives may be varied over a wide range. The effects of the voids in pressed granular explosives may be enumerated as follows:

1. A large increase in effective surface area which makes the material more ignitable and increases the mass reaction rate for a given surface burning rate.

2. An increase in the overall compressibility and the proportion of the energy of a shock converted to interstitial heat. The result is that much weaker shocks can cause reactions of sufficient vigor to propagate as detonations.

3. An increase in the effective free volume with the result that a given reaction rate results in a slower pressure rise and thus tends toward less rapid acceleration of the reaction.

4. A decrease in the velocity and pressure of stable detonation with increasing percentage voids.

5. A reduction in the "acoustic impedance" both because of the reduced density and the increased compressibility. This results in an improvement of shock transmission between the explosive and low impedance media such as air and deterioration of shock communication with high impedance media such as steel.

It is quite plain that these effects may reinforce or counteract one another in their influence upon the transmission of detonation depending upon circumstances.

Most primary explosives depend upon a combination of the first two of these effects to promote the transition from burning to detonation. When pressed to a density above a limit characteristic of the explosive they refuse to effect this transition. This phenomenon is known as "dead pressing". It has been stated frequently that mercury fulminate is dead pressed at loading pressures in excess of 25,000 psi. Some of the present authors have shown that this figure may vary from 5,000 to 80,000 psi depending upon

conditions of confinement. Lead azide shows less tendency than other explosives to "dead press" probably because its extreme hardness results in quite high percentages of voids at practical loading pressures. However, "dead pressing" effects have been observed with lead azide and may cause trouble where confinement is poor, particularly if the lead azide has been loaded in a high humidity atmosphere. Where "dead pressing" is not a factor, the third and fourth effects mentioned above result in a general increase in the effectiveness of donors with increasing density.

The manner in which these effects combine to determine the sensitivity of an acceptor is quite obvious when considered qualitatively. Quantitative consideration of the effect of density on the transmission of detonation has not been undertaken. The combined effects can be observed experimentally but it is difficult to separate them. In air gap experiments, the apparent sensitivity decreases with increasing density within the usual range of densities used in ordnance. Where barriers of other materials are involved, this relationship may change. In Figure 7 the effect of density on critical gap is compared with that on critical aluminum barrier. Note that the air gap varies much more sharply with density than does the barrier. Dodd[12] found that, with combined air gaps and steel barriers, the optimum density of tetryl as an acceptor was in the neighborhood of 1.5.
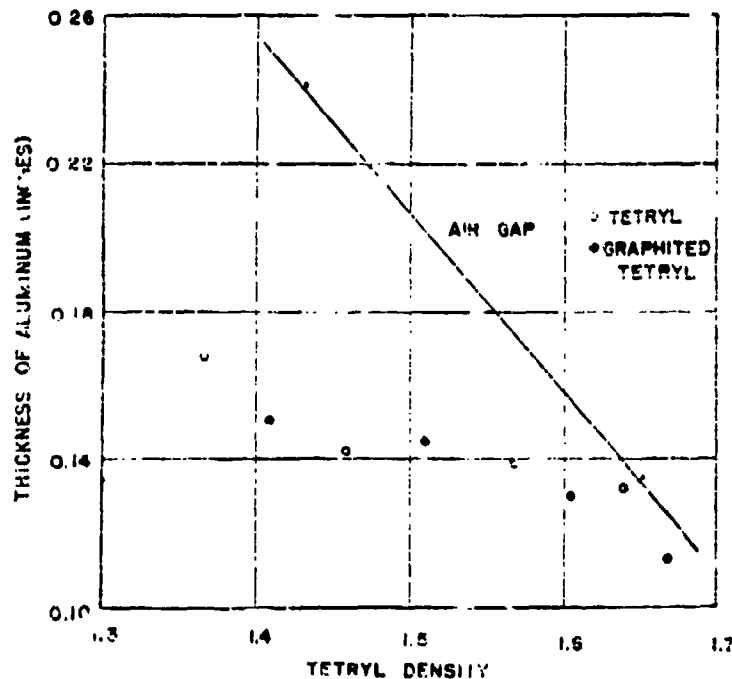
Figure 7

Propagation of Detonation Lead Azide to Tetryl

In explosives loaded to densities lower than is the usual ordnance practice, the growth of detonation is slower and the line between "fires" and "misfires" becomes more nebulous. The choice of criterion of fire can have a substantial effect upon the estimate of the critical gap, Figure 8.
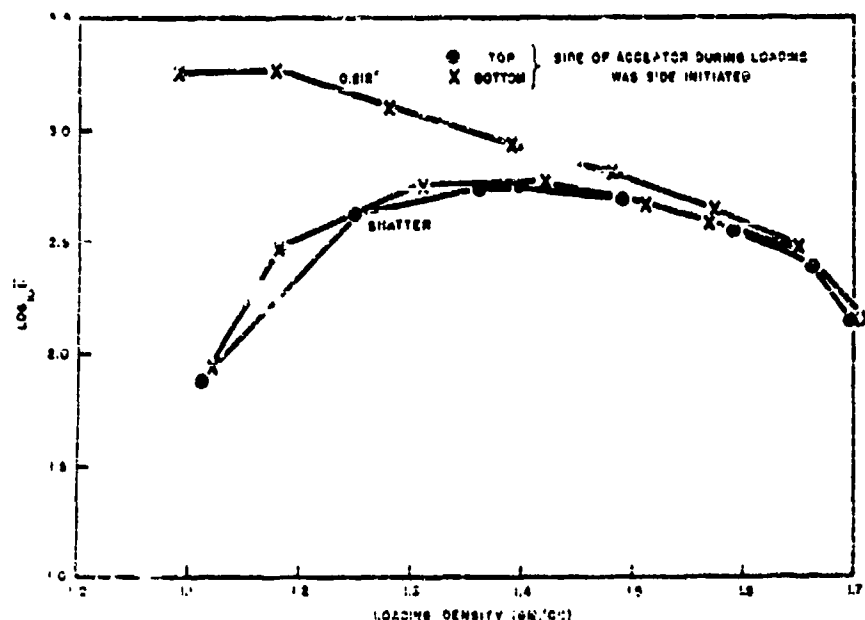
Figure 8*
Dependence of Air Gap Sensitivity of Tetryl Upon Loading Density
and Criterion of Fire

*Regular Bruceton type air gap sensitivity tests were performed with donors of PETN loaded at pressures of 10,000 psi and acceptors of tetryl loaded at pressures varying from 500 to 80,000 psi. Note that for the lower densities there is a complete reversal in the order of sensitivity with density when the criterion of the Bruceton test is varied from one requiring that the acceptor container be shattered to one requiring that the end of the explosive cavity farthest from the donor be expanded from 0.200 inches to 0.212 inches diameter.

CONFIDENTIAL

Similarly particle size affects on the transmission of
detonation may be taken as evidence of the role of surface burning
in incipient and growing detonation. In an investigation of such
effects coarse sieve cuts were invariably less sensitive to
initiation than fine cuts of eight different lots of tetryl[13].
Typically, the critical gap for the initiation of tetryl which was
held on a number 35 sieve was 0.128 inches while that for tetryl of
the same lot which passed through a number 45 screen was 0.150 inches.

Cast charges are less sensitive than pressed charges of the same
explosive. The difference is more than can be explained in terms of
loading density. Eyster, Smith, and Walton[8] report 0.82 inches for
the critical thickness of wax barrier for the initiation of cast TNT
(density 1.60) and 1.68 inches for pressed TNT (density 1.55). The
grain size of cast explosives affects their sensitivity, in a manner
similar to that of the particle size of pressed explosives. In
minimum booster tests carried out by present authors[14] a booster
of 9.3 grams of tetryl was required to initiate TNT cast at 100°C
under conditions where "creamed" TNT, cast at its melting point, was
initiated by 8.3 grams of tetryl. The crystals of TNT in the case of
the hot charges were of the order of an inch in length, while those
in the creamed material were microscopic.

Factors Related to Confinement

Rather few explosive experiments are carried on in vacua.
Explosive charges are generally bounded by inert (non-explosive)
media. Whenever a detonation reaches a boundary the shock is
transmitted to the adjacent medium, with a resultant displacement of
the interface between the explosive and the inert medium. Similarly,
the more gradually rising pressure associated with growing
deflagration can cause motion of the interface. When a wave such as
a shock is transmitted from one medium to another the concept of
impedance coupling is useful. The characteristic acoustic impedance
of a medium is defined as the product of its density and the velocity
at which sound propagates in it. Similarly, the characteristic
shock impedance of a medium might be defined as the product of the
density and the velocity at which a shock propagates in the medium.
The variation of shock with amplitude is reflected in a variation of
the shock impedance. A rigorous treatment taking this variation
into account would be severely limited by the lack of equation of
state data in the pressure range associated with detonation
phenomena. For some materials, information is available regarding
the velocities of shocks of this strength. For these a useful
approximation is the assumption that the velocity is constant for
that part of the shock wave which is important in the propagation
of detonation.

In another paper of this conference[15] it is shown that the
length of the head of reaction products behind the detonation front
of a confined column of explosive is directly related to the shock

CONFIDENTIAL

impedance of the confining medium. As mentioned above, the length of the detonation head of the donor can have an effect on the transmission of detonation. In one experiment[13], lead azide donors 0.10 inches in diameter, confined in steel and brass, initiated tetryl acceptors across mean gaps of 0.057 inches and 0.050 inches respectively while those confined in aluminum would initiate the same acceptors across a mean gap of only 0.030 inches. The shock impedances of steel, brass, and aluminum are 4.2, 3.9, and 1.7 megarayls* respectively.

As pointed out in the introduction, the growth of detonation in the acceptor depends upon an increase in pressure resulting from the excess of gaseous products and heat produced by the reaction over losses, which are associated with expansion. In an air gap test the rearward expansion of the reaction products of a recently initiated acceptor is retarded by the presence of the donor product gases to an extent related to their mass and density. The resistance of the confining medium to radial expansion is related to its shock impedance. Table II gives critical air gaps obtained with a series of systems which were made as similar as possible except for the confining medium of the acceptor. Also given are shock impedances of the acceptor materials as obtained by Slie[15].

Confining Medium of Acceptor	Shock Impedance of Acceptor Confinement[15] (megarayls)	Critical Air Gap[16] (lead azide to tetryl) (0.150 inch diam. columns)
Lucite	0.7	0.063 inches
Magnesium	1.4	0.088 "
Zinc (die cast)	2.6	0.101 "
Babbitt	3.2	0.103 "
Bronze	4.2	0.105 "
Brass	3.9	0.153 "
Steel (SAE 1020)	4.2	0.160 "

Table I
Critical Air Gaps Related to Acoustic Impedance of
Acceptor Confining Medium

The effect of confinement upon acceptor sensitivity varies with the explosive material. Table III, from some measurements of Dimmock[17], gives critical gaps obtained for a number of acceptor explosives using two systems which differed mainly in the confinement of the acceptor. Note the inversions between tetryl and RDX and between TNT and Comp A.

- -

*One rayl or acoustic ohm is equal to one gram per square centimeter per second.

CONFIDENTIAL

Acceptor Explosive	Acceptor Confinement	
Material	Brass	Aluminum
Comp A	0.046 inches	0.017 inches
TNT	0.049 "	< 0.010 "
Comp B	0.062 "	0.039 "
Tetryl	0.062 "	0.061 "
RDX	0.101 "	0.050 "

Table III
Critical Gaps for Various Explosives for Two Confinements

The above discussion has concerned itself with the effects of confinement of explosives by containers so thick that they may be considered to be infinite. No systematic data are at hand regarding the effect of confinement in thinner walled vessels upon the transmission of detonation. The scattered data which are at hand suggest to the authors that, as in most confinement effects, the sensitivity or effectiveness rises sharply with thickness at first and approaches a maximum at a point where the wall thickness is of the order of the diameter of the explosive column.

Confinement of an air gap between two explosive charges can have a very large effect upon the critical length of such a gap. Notice the order of magnitude difference between the confined gaps used in the experiments illustrated in Figure 5, and the unconfined gaps associated elsewhere in this paper with explosive charges of the same size. Here again systematic data are lacking. Dodd[12] showed that, for one system, a gap smaller in diameter than the donor resulted in more effective transmission of detonation than one much larger. Using another system, one of the present authors showed that a gap equal to or slightly larger than the donor resulted in more reliable transmission than a gap somewhat smaller in diameter than the donor. With still another system, others of the present authors could detect no difference between a gap confined in a tube slightly larger than the donor and one three times the diameter of the donor. In all three of these experiments, the donors were detonators with metal cups and additional barriers were involved.

Factors Involving the Nature of the Separation Between the Charges

Most of the experiments discussed above are determinations of critical air gaps between coaxial cylinders of explosive. Although this type of experiment is a convenient tool for the investigation of the effects of many of the factors involved in the transmission of detonation, most practical transmission problems involve more complex systems. The permutations of the interactions involved in such systems are overwhelming in number. The data available are too diverse and "spotty" to give a clear, connected picture. Some of

CONFIDENTIAL

them, however, are quite revealing.

The transmission of detonation between two separated charges involves the transmission of a shock wave from the donor explosive to the intervening medium, through the medium, and to the acceptor explosive. Unless the shock impedance of the intervening medium is an exact match to that of the explosive, the shock must be partially reflected, either as a shock or as a rarefaction, at the interface. Either type of reflection will cause the energy of the transmitted wave to be less than that of the incident wave.

The application of the concept of impedance coupling to detonation transmission and the limitations of this application may be illustrated using some data of Eyster, Smith, and Walton[8]. Determinations were made of the critical barrier through which detonation could be transmitted from tetryl boosters to various explosives. Measurements were also made of the dents made in steel by tetryl boosters from which they were separated by various thicknesses of the same barrier materials. By interpolation, these data may be used to obtain the depth of dent produced by a combination of booster and barrier which will initiate a given explosive 50% of the time. This depth varies with the barrier material. If it is assumed that the shock energy which must be transmitted to the explosive in order to initiate it is independent of the transmission medium and that the depth of dent produced is a direct measure of the energy transmitted to the steel block, impedance coupling principles may be used to compute the relative depth of dent which should be associated with 50% functioning. Table IV gives the critical barrier thicknesses for the initiation of Comp B together with the corresponding depth of dent as interpolated from experimental data and as computed using impedance coupling considerations.

Barrier Material	Comp B Acceptor Barrier Thickness (50% Point)	Corresponding Dent Int.*	Corresponding Dent Comp**
Air	1.21	0.039	0.006
Wax	1.46	0.013	0.007
Aluminum	1.51	0.0195	***
Copper	1.17	0.032	0.031
Polystyrene	1.43	0.0115	0.0115
Wood (oak)	1.04	0.035	0.0093

Table IV

Critical Barriers of Various Materials with Corresponding
Dents Produced in Steel Plates

*Interpolated from experimental data. **Computed using impedance coupling principles. ***The dent produced by the 50% combination of booster and aluminum barrier was used in the computation of the computed barrier thickness of other materials.

CONFIDENTIAL

It will be noted that the experimental and computed values give very good agreement between aluminum, copper, and polystyrene and somewhat worse for wax, while the experimental values for air and wood are completely out of line. The poor agreement for the wax barrier may reflect the lack of equation of state data for this material. As pointed out earlier in this paper, the phenomena associated with the transmission of detonation across air gaps is too complex to be characterized in terms of simple impedance coupling. Apparently this observation also applies to wood.

In some cases air gaps and barriers are combined. A special case of combined barriers and gaps is that in which a relatively thin solid barrier is in direct contact with the donor explosive and is followed by a gap. Under these circumstances, the barrier material which is hurled across the gap plays an important role in the initiation of the acceptor. Since it takes some distance of travel for the solid material to reach its maximum velocity, the most favorable conditions for transmission of detonation involve an optimum gap. Dodd[12] found that the optimum gap for one such system was about 1/16 of an inch. Grumman and Robertson[18] in another system, involving transmission between a detonator and a lead, found that the optimum was in the neighborhood of 1/8 of an inch, while some of the present authors, in a system involving the initiation of HBX by a booster, found that the optimum was in excess of a quarter of an inch. The data in Table V were obtained in some experiments directed toward determination of the critical length of booster for the initiation of cast TNT. In these tests, the booster was well confined both radially and from the rear. The booster cups of aluminum and of steel had bottoms about 0.070 inches thick. All boosters were a mixture of RDX and wax (97/3). In each test the thickness of booster for 50% initiation was determined by a variant of the Bruceton method.

Standoff Distance	Booster Length for 50% Initiation of TNT	
	Steel Cup	Aluminum Cup
0.000	0.347 inches	0.238 inches
0.050	0.325 "	0.181 "
0.100	0.215 "	------

Table V
Minimum Booster Length for Initiation of TNT at
Various Standoff Distances

An interesting feature of the results obtained with the steel booster cup is the substantial change in booster requirement as the gap was increased from 0.050 to 0.100 inches although the booster length needed with zero gap was not very different from that with 0.050 gap. An explanation which has been proposed for this effect is that the velocity of the bottom of the cup increases in steps as

17 CONFIDENTIAL

CONFIDENTIAL

it reverberates. Note that smaller boosters are required when aluminum cups are used. In another experiment[14] where determinations were made of the critical thickness of a second barrier of steel which was in direct contact with an HBX acceptor, this thickness was found to be 0.236 inches when aluminum cups were used and 0.400 inches when brass cups were used. Where a gap is interposed between a donor and an acceptor a barrier in contact with the donor can help bridge it and where a barrier is interposed a gap beyond it is conducive to improved transmission of detonation. Perhaps more surprisingly, it was observed that a tetryl booster which failed to initiate a charge of TNT when in direct contact with it in three consecutive trials caused high order detonation in eight of nine trials when an air gap was interposed.

When the donor is displaced from its alignment with the acceptor as shown in Figure 9 the transmission of detonation from donor to acceptor becomes more difficult. In Figure 10 the critical transverse displacements for the transmission of detonation between donors of lead azide and mercury fulminate and acceptors of various high explosives are graphically compared with critical axial air gaps for the same combinations of explosives. The "S" shape of these curves is apparently related to the point at which the expanded hole in which the donor charge had been loaded is tangent to the unexploded acceptor explosive. The initiation of some explosives, including tetryl, is apparently quite probable when the holes overlap, but quite improbable when they do not. This fact suggests that the initiation is related to contact with the acceptor explosive of the hot gases produced by the reaction of the donor explosive. For the more sensitive high explosives such as RDX and PETN the metal borne shock is apparently an important initiation mechanism. The deformation of the containers of these explosives sometimes showed evidence that initiation occurred at a point other than the end.
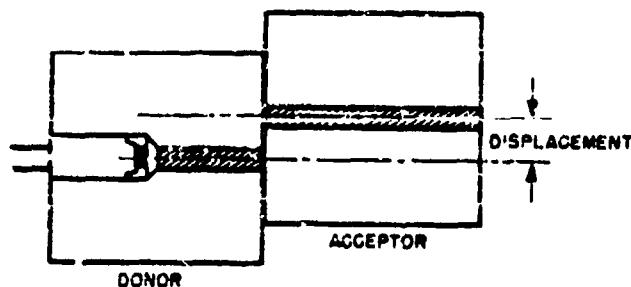
Figure 9
Arrangement of Donor and Acceptor in the Transverse
Displacement Tests
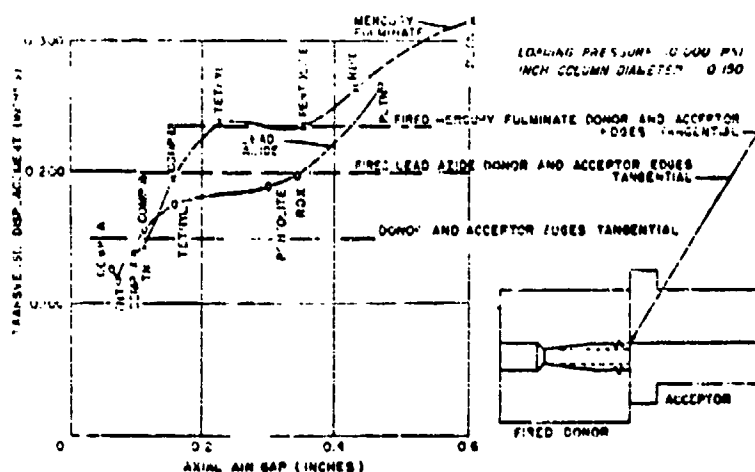
Figure 10
Initiation Properties of the Explosive Across Transverse
Displacement and Axial Air Gaps

In some cases explosive charges are initiated by means of
smaller charges which are inserted in holes in the acceptor charges.
This type of system may be quite effective. Army Engineer Corps
special blasting caps of an old lot which were incapable of
initiating Comp B charges reliably from any external position
initiated the same charges quite reliably when inserted only
0.2 inches in holes over an inch deep. These results were obtained
with holes ranging in diameter from 5/16 inch, which is a sloppy
clearance fit, to 1/2 inch. Other evidence is also at hand which
indicated that this type of initiation can be quite effective.

Factors Involving Special Geometry

One way in which detonation is transferred from one element
to the next is by the use of the shaped charge principle in the
so called "spit back" fuze. In the shaped charge a special shape is
used on the end of the detonator which has the form of a cone with
the apex pointing into the detonator. The detonation, upon reaching
this cone causes it to collapse and forms a jet which concentrates
the energy and makes it effective at considerable distances. This
is used in certain applications in which it is desired to have a
detonator in the nose of a shell initiate a booster in the rear.
It should be pointed out that, since the shaped charge action is one
of concentrating the energy put out by the detonator, the problem of
aiming the jet becomes critical. If this jet does not strike the

booster properly it will, of course, not initiate it. It should also
be pointed out that, under some circumstances the concentration of the
energy in two dimensions by a shaped charge can result in greatly
increased dispersion in the third. Where initiation is marginal
because of the small diameter of the donor, the use of a shaped
charge can result in complete failure[19]. Such failures are
characterized by extremely deep narrow holes in the acceptor.

Use has also been made of the shape of the boundary between
two explosives loaded into the same element to control the form of
the detonation wave as it reaches the exit end of the element. If a
detonator, for instance, contains two explosive materials, the first
having a detonation velocity less than that of the second, a curved
interface, figure 11, between the two explosives can be used to
reduce the curvature of the detonation wave as it diverges from the
point of initiation. If properly designed this could give a plane
or converging wave at the exit end of the element.
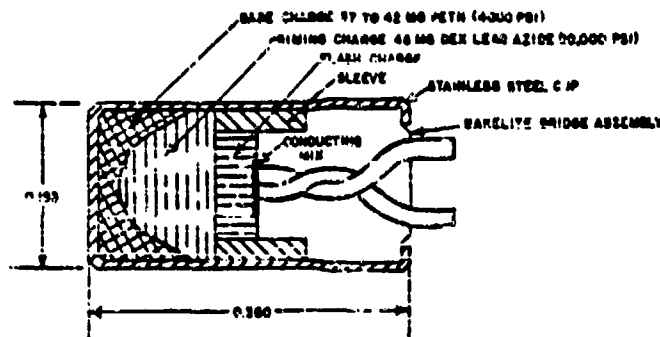
Figure 11
Eastman Form Charge Detonator

Conclusions

A number of reasonable mechanisms have been proposed for the
transmission and growth of detonation, and for the losses which
oppose these processes. The temptation exists to propose a
mechanism, preferably one which can be reduced to manageable
mathematics, and to try to explain all observable phenomena in
terms thereof. The most emphatic conclusion which can be drawn
from the observations discussed above is that yielding to any such
temptation can lead only to confusion.

The transmission and growth of detonation involves a series of
chemical and physical processes, each quite simple in itself, which

CONFIDENTIAL

interact differently under different circumstances. These
conclusions are generalities. More specific conclusions may be
found above.

CONFIDENTIAL

CONFIDENTIAL

References

(1) Third International Symposium on Combustion and Flame and
     Explosion Phenomena, Williams and Wilkins, Baltimore, 1949,
     Initiation of Detonation of Explosives, pg. 560,
     G.B. Kistiakowski

(2) Cambridge University Press, 1952, The Initiation and Growth
     of Explosions in Liquids and Solids, F.P. Bowden and
     A.D. Yoffe

(3) Chemical Reviews, Vol 45, pp. 69-181, The Stability of
     Detonation, H. Eyring, R.E. Powell, G.H. Duffey, and
     R.B. Parlin

(4) Comptes Rendus de l'Academie des Sciences de l'URSS, 1946,
     Vol. 51, No. 1, pp. 29-32, On the Dependence of the Burning
     Velocity of Secondary and Initiating Explosives Upon the
     Pressure, K.K. Andreev

(5) NAVORD Report 90-47, Theory of the Detonation Process,
     R.J. Finkelstein and G. Gamow, 20 April 1947

(6) AMP Report No. 101.1R, OSRD Report 4040, Statistical
     Analysis for a New Procedure in Sensitivity Experiments,
     Statistical Research Group, Princeton University, July 1944

(7) NOLR 1111, Ordnance Explosive Train Designers' Handbook,
     April 1952

(8) NOLM 10336, The Sensitivity of High Explosives to Pure Shocks,
     E.H. Eyster, L.C. Smith and S.R. Walton, 14 July 1949

(9) NAVORD Report 2285, Shock Velocities in the Immediate
     Neighborhood of Detonating Explosives, R.H. Stresau
     and J. Savitt, 27 December 1951

(10) Electric Detonator Symposium, Franklin Institute, September,
     1954, Factors Affecting the Output of Electric Detonators,
     R.H. Stresau, L.D. Hampton, J. Savitt and W.M. Slie

(11) NAVORD Report 2844, The Propagation of Detonation in Some
     Special Explosive Systems, J. Savitt, 13 April 1953

(12) Ordnance Board Proceedings No. 30878 with enclosure dated
     15 April 1945

(13) NAVORD Report 2385, Investigation of the Propagation of
     Detonation Between Small Confined Explosive Charges, Progress
     Report, W.E. Dimock, L.D. Hampton and L.E. Starr,
     1 April 1952

CONFIDENTIAL

Hampton, Savitt, Starr, Stresau

CONFIDENTIAL

sous

(14)   Unpublished Results of the Present Authors.

(15)   Second ONR Detonation Conference, February 1955, Conditions
        Behind the Reaction Zone of Confined Columns of Explosives,
        Notions Derived from Plate Dent Experiments, R.H. Stresau
        and W.M. Slie

(16)   NAVORD Report 2938, Effect of Acceptor Explosive Confinement
        Upon Acceptor Sensitivity, J. Savitt, 13 November 1953

(17)   NAVORD Report 2494, A Small Scale Gap Sensitivity Test,
        W.E. Dimmock, 2 July 1952

(18)   NOLM 9707, The Effect of Air Gaps on the Initiation of a
        Lead by a Detonator, R.L. Graumann and A.E. Robertson,
        25 June 1948

(19)   NAVORD Report 2134, Studies of the Propagation of Detonation
        Through Barriers Separated by Air Gaps, W.E. Dimmock,
        L.D. Hampton and R.H. Stresau, 29 June 1951

CONFIDENTIAL

THE CORRELATION OF THE SENSITIVENESS OF EXPLOSIVES WITH COMBUSTION DATA
2

B. G. Whitbread & L. A. Wiseman
Explosives Research & Development Establishment
Ministry of Supply, England

SUMMARY.

During the last few years at E.R.D.E. the sensitiveness of a large number of liquid explosives, and of a few solid explosives, has been determined by the gap test, in which the explosive is subjected to a shock wave. It is shown that the sensitiveness of liquid explosives, measured in this way, can be correlated with the product, $\dot{m} \times Q$, where $\dot{m}$ is the mass rate of combustion at an arbitrary pressure of 50 atms, and Q is a calculated heat of explosion. It appears also that, for a given value of $\dot{m} \times Q$, sensitiveness increases with increasing value of ρQ, where ρ is the density of the explosive.

These results have been interpreted in terms of the following model. It is assumed that the shock wave initiates a combustion reaction in some region of the liquid explosive; the mechanism and location of the initiation is not yet known. In order to produce a positive effect, i.e. an explosive increase in pressure or a reactive shock wave, it is necessary for the pressure in this combustion region to increase rapidly and it is shown that the rate of increase of pressure depends directly on $\dot{m} \times Q$, ρQ, and the pressure, and inversely on the linear dimensions of the combustion region.

The product, $\dot{m} \times Q$, gives a broad correlation with sensitiveness over the range of explosives from those as inert as ethyl nitrate and T.N.T. to those as sensitive as the initiator class. It fails, in this simple form, with plastic propellants but it is shown that this apparent lack of correlation may arise from the particular type of dependence of rate of burning on pressure. T.N.T. and Picric Acid have been examined in greater detail. The sensitiveness of liquid T.N.T. at $90^\circ C$ and of pressed charges of granular T.N.T. of different grain sizes over a range of densities have been measured. It is shown that the sensitiveness of pressed charges of T.N.T. (and of Picric Acid) can be interpreted in terms of cavity initiation, i.e. "hot spots" created by the adiabatic compression of gases in a

cavity. In the pressed charges so far examined, initiation of the combustion reaction is the controlling process whereas, for liquid explosives, initiation appears to be easy, and growth (the rate of increase of pressure in the combustion domain) is the controlling process. Liquid and solid T.N.T. at the same density, are about equally sensitive on both the gap test scales used in this work. This agreement is shown to be fortuitous and this deduction was later confirmed by measurements of the sensitiveness of liquid and solid Picric Acid.

The correlation of the rifle bullet sensitiveness of liquid explosives with the gap test sensitiveness suggests that the rifle bullet initiates a combustion reaction. This idea is supported by the different behaviour of plastic propellants when subjected to the rifle bullet test and to the gap test.

The initiation process in liquid explosives, when assessed by the gap test, is discussed in the light of this experimental work and the negative conclusions reached that the initiation is not due to the presence of small air bubbles or to density fluctuations in the liquid. The mechanism, whereby a low-order detonation is propagated in a liquid explosive, remains a mystery.

The relationship between sensitiveness as measured by the gap test and by other tests, such as the impact test, is discussed. In order to be able to do this, some measurements of the conditions in the gap test have been made. The shock pressures necessary to produce an explosion or reactive shock in the explosive have been measured, and it is deduced from the results on granular explosive charges, that the "effective" duration of the pressure pulse increases with increasing pressure and that this factor must be taken into account when assessing the results of the gap test.

The object of this work was to obtain a detailed knowledge of the initiation and growth processes in explosion phenomena, so that the possibilities of more efficient desensitisation of explosives could be assessed. For homogeneous solid and liquid explosives, the "intrinsic" sensitiveness can be assessed from the sar rate of burning, which is a measurable property. It appears to be difficult if not impossible, to lower the rate of burning, except by reducing the energy, which is clearly undesirable. We must, therefore, concentrate on studying the effect of the physical state of the explosive on its sensitiveness. For liquid explosives we propose to study the effect of increasing viscosity on sensitiveness. In the case of solids, energy can be concentrated locally by friction, by stress concentration and by adiabatic compression of trapped air. Some of these factors may be controllable by altering crystal habits and crystal sizes. The role of desensitisers, such as wax, is discussed and it is suggested that smaller quantities, i.e. less than the customary 10 - 15 per cent, might be effective if the surfaces of the individual crystals of the explosive can be

Confidential.

completely covered with the wax.

It is known that, for a given value of Q, the rates of burning of explosive compounds decrease in the sequence: nitramines, nitroxy-compounds 1 nitro-compounds. It would, therefore, appear to be worthwhile exploring the field of nitro-compounds, particularly of the aliphatic series, more thoroughly.

----

1.   INTRODUCTION.

Any discussion of the sensitiveness of explosives must consider two main factors:

(a)   the mechanism by which mechanical energy (in the case of initiation by impact, shock wave or friction) or electrical energy (in the case of spark initiation) is converted into thermal energy, or initiates some reaction which releases thermal energy, and

(b)   the conditions under which a "hot spot", i.e. a localised region at a higher temperature than the bulk explosive, will be formed and grow until an explosive reaction ensues.

This paper is concerned primarily with the second of these features.

The conception of hot spots is by no means new (c.f. Bowden and Yoffe, ref 15), and one of the earliest attempts to put it on a quantitative basis was made by Rideal and Robertson (1) who studied the minimum size and temperature of a region in an explosive material in which the rate of production of heat would be greater than the rate of loss of heat by conduction, to the rest of the explosive. In this, values of the rate of decomposition of the explosive are required under conditions which admit only of gross extrapolation of low temperature kinetic data.

Another approach to this problem was made by Adams and Wiseman (2) in their consideration of initiation of explosive reaction by adiabatic compression of a cavity within an explosive. It is clear that an exothermic reaction, under conditions such that the rate of production of heat is greater than the rate of loss of heat, will eventually become a combustion reaction. These authors, therefore,

Confidential.

Confidential.

considered the conditions necessary to initiate a combustion reaction over the surface of the cavity and showed that the important properties of the explosive were the heat of explosion, Q (cal/g) and the mass rate of burning, $\dot{m}$(g/cm.^{2} sec). It was shown that the sensitiveness of the explosive to this type of initiation increased with increasing values of the quotient, $\dot{m}$/Q.

In order to put sensitiveness studies on a more quantitative basis, it was decided at E.R.D.E. some years ago, to study the sensitiveness of explosives to shock waves by the Gap Test (3). In an analysis of these results (4) it was shown that the sensitiveness of liquid explosives measured by this test, could be correlated with the product $\dot{m}$ x Q, where $\dot{m}$ was measured at an arbitrary pressure of 50 atm.

This report is an attempt to clarify the present position of the application of these concepts, involving rates of burning, to sensitiveness and it falls into the following sections:-

(a) an analysis of the range of validity of the product, $\dot{m}$ x Q, as a measure of sensitiveness,

(b) an examination of the significance of the gap test,

(c) an experimental approach to the correlation of the sensitiveness of liquid and solid explosives with each other, and

(d) some tentative suggestions on the mechanism of initiation and growth of explosive reactions.

2. VALIDITY OF CORRELATION FACTOR, $\dot{m}$ x Q.

The important factor in this correlation is the rate of burning, since Q for weak and strong explosives does not vary by more than a factor of about 5, whereas $\dot{m}$ can vary by a factor of at least 30 in liquid explosives (the difference between methyl nitrate and propyl nitrate) and by a factor of about 1000 between an initiator, such as mercury fulminate, and a weak explosive such as ethyl nitrate. The uncertainty in the value of Q is, therefore, relatively unimportant. Q, in this paper is calculated for the hypothetical reaction (at constant pressure).

$$C_xO_y H_z N_w = xCO + (y - x) H_2O(g) + (\tfrac{1}{2}z + x - y) H_2 + \tfrac{1}{2}w N_2$$

If there is more than sufficient oxygen to oxidise all the carbon and hydrogen, it is used to oxidise the CO to CO_2. Theoretically, the heat of explosion should be calculated as for a constant volume explosion but, since the products in transient reactions are not as simple as those indicated above, there would be no gain in accuracy in so doing and we have, therefore, used Q calculated by the simple process given above. The heats of formation used are given in Appendix 1.

Confidential.

At what pressure to compare the rates of burning is not known (this is discussed later). We have used 50 atms., where data is available, but in the case of initiators, it has been necessary to use a reference pressure of 1 atm.

2.1 Liquid Explosives.

Many of these have been assessed for sensitiveness at E.R.D.E. under two arbitrarily chosen conditions of confinement:- Scale I and Scale III. (Scale II has been used for only a few cases, which are referred to later). The details of these scales are given in Ref 3, but for this discussion it is sufficient to know that Scale III represents the "heavier" confinement, and that a larger initiating charge is used which delivers a greater impulse to the test assembly. The results for Scale III are shown in Table I and Fig. 1.

The other simple forms of correlation are with Q, with $\dot{m}$ and with $\dot{m}/Q$. Correlation with Q is good for the organic nitrates but does not extend to these mixtures containing nitro compounds or to the Dithekites (stoichiometric mixtures of nitrobenzene and nitric acid, with added water). Correlation with $\dot{m}/Q$ is bad, while that with $\dot{m}$ is fair but not as good as that with $\dot{m} \times Q$.

Provisionally, therefore, we shall accept that the product, $\dot{m} \times Q$, is the best correlation factor. In reference 4, it was suggested that, on the available combustion data, the dinitrate of butane 2:3 diol should be less sensitive than ethyl nitrate. This was found not to be true. A possible reason for this will be discussed later.

The results for Scale I are shown in Table II and Fig II.

On Scale I results with C (the card value) greater than 50 cards are not reproducible and the effect with C less than 5 cards is not a pure shock initiation since hot particles from the donor are known, by photographic observation, to penetrate the gap under these conditions. The main anomaly is the apparently large difference between the sensitiveness of butane 2:3 diol dinitrate and the 75/25 (w/w) mixture of ethylene glycol dinitrate and triacetin. These two explosives have about the same density, heat of explosion and rate of burning. A possible explanation of this is that Scale I only gives a significant result when the rate of growth of the explosion centre from the point of initiation is sufficiently fast. If two explosives can be initiated with equal ease but in one the growth, i.e. rate of increase in pressure, is faster than in the other then, since the criterion is the damage done to the container, the one in which the rate of growth is faster will appear to be more sensitive by this test. From Fig 2 it will be seen that, for a given value of $\dot{m} \times Q$, the explosive having the higher value of Q is the more sensitive. In fact, with C greater than 20, the sensitiveness correlates better with Q than $\dot{m} \times Q$. However, correlation with Q cannot accommodate

Confidential.

T A B L E I.

SENSITIVENESS OF LIQUID EXPLOSIVES ON SCALE ILI.

(m at a combustion pressure of 50 atms.).

Explosive.		ρ	Q	R_v	$\dot{m}$	C	$\dot{m} \times Q$
Component A.	Component B.	g/cm^3	cal/g	cm/sec	g/cm^2 sec		cal/cm^2 sec
Ethyl Nitrate.	Ethyl Alcohol.						
1. 100	0	1.11	754	0.37	.41	43	309
2. 96	4	1.09	662	0.31	.34	35	225
3. 92.1	7.9	1.08	572	0.26	.28	29	160
4. 90.4	9.6	1.07	534	0.24	.255	28	136
5. 84.1	15.9	1.05	388	0.18	.19	22	74
6. 80.1	19.9	1.03	297	0.14	.145	19	43
Ethyl Nitrate.	Propyl Nitrate.						
7. 80	20	1.10	662	0.29	.32	37	201
8. 70	30	1.10	603	0.26	.285	31	172
9. 60	40	1.09	570	0.23	.25	27	142
10. 0	100	1.05	294	0.14	.145	16	43
Ethyl Nitrate.	Nitromethane.						
11. 60	40	1.12	840	0.19	.21	31	176
12. 40	60	1.13	883	0.15	.17	29	150
13. 0	100	1.14	969	0.10	.115	24	111
Ethyl Nitrate.	Nitromixture.[x]						
14. 80	20	1.11	757	0.24	.265	35	201
15. 70	30	1.12	759	0.19	.215	29	163
16. 60	40	1.12	761	0.16	.18	27	137
Butylene 2:3 glycol dinitrate.	Ethyl Alcohol.						
17. 96	4	1.27	729	0.15	.191	40	139
18. 92.1	7.9	1.24	637	0.121	.150	31	96
19. 90.4	9.6	1.23	596	0.109	.134	29	80
20. 84.1	15.9	1.18	450	0.078	.092	22	41
21. 80.1	19.9	1.16	353	0.063	.075	18	26
Nitroglycerine.	Triacetin.						
22. 67.5	32.5	1.41	656	0.175	.247	29	162
23. 65	35	1.40	592	0.150	.210	24	124
24. 60	40	1.37	464	0.104	.142	16	66
25. 55	45	1.36	336	0.074	.101	11	34
26. Dithekite D13 (contains 13% w/w H_2O)		1.37	1265	-	-	30	-
27. Dithekite D20 (contains 20% w/w H_2O)		1.36	1146	-	-	19	-

[x] C is a measure of the thickness of the gap. The gap consists of cards and C is the number of cards in the gap.

[x] Nitromixture = 83% nitromethane + 17% 2-nitropropane (w/w).

Confidential.

T A B L E II.

SENSITIVENESS OF LIQUID EXPLOSIVES ON SCALE I.

(ṁ at a combustion pressure of 50 atms).

	Explosive.		ξ g/cm³	Q cal/g	E_D cm/sec	ṁ g/cm² sec	C	ṁxQ cal/cm² sec
	Component A.	Component B.						
	Nitroglycerine.	Triacetin.						
1.	90	10	1.54	1286	1.02	(1.51)	65	1941
2.	85	15	1.50	1124	.69	(0.96)	47	1060
3.	82.5	17.5	1.49	1049	.54	(0.78)	31	816
4.	80	20	1.47	970	.44	.65	26	630
5.	75	25	1.45	811	.29	.42	22	341
6.	70	30	1.42	694	.21	.285	3	185
	Ethylene Glycol Dinitrate.	Triacetin.						
7.	89	11	1.45	1267	.56	.81	52	1037
8.	84	16	1.43	1108	.43	.63	29	683
9.	80	20	1.41	987	.305	.43	27	429
10.	75	25	1.39	838	.215	.30	21	254
	Ethyl Nitrate.		1.11	754	.37	0.41	2	309
	Nitromethane.		1.14	969	.10	.115	3	111
	Dithekite D20.		(1.56)	1146	-	-	4	(60) [x]
	Dithekite D13.		1.57	1265	-	-	16	(160) [x]
	Butane 2:3 diol dinitrate.		1.303	815	.22	.285	6	232
	P.E.C.N.		1.39	989	.61	.85	27	841

[x] ṁ x Q value from Fig. 1

Dithekite D20 or D13.

2.2 Rates of Burning of Liquid Explosives.

The values of ṁ quoted in Table I and Table II are for a combustion pressure of 50 atms. The sources of this information are in references 5, 6, 7 and 8. Values in brackets were obtained by extrapolation of the plot of log ṁ against Q. Values for the series based on the dinitrate of butane 2:3 diol were obtained from the results on the other glycol dinitrates (ref 7) since the log ṁ value gives a linear relationship with Q.

The values of ṁ have been deduced from the linear rate of regression of the liquid meniscus when the liquid burns in a capillary tube. There is, therefore, some uncertainty in the value of ṁ since it is not known whether the flame zone is parallel to the meniscus or flat and perpendicular to axis of the tube in which the

Confidential.

Confidential.

liquid is burnt. Furthermore, the shape of the meniscus varies some-
what with pressure and nature of the explosive: there is, therefore,
both an absolute and a relative uncertainty in the values of h. This
aspect has been considered by Stocks (6) but we propose to ignore it
in the treatment of this report since the uncertainty in the rate of
burning is of about the same order as the uncertainty in Q.

It is shown later that the shock pressures in gap test initiation
are of the order of 10^4 atms. If the rates of burning depend linearly
on the pressure, any reference pressure, e.g. 50 atms, can be used to
compare the magnitude of the product, $\dot{m} \times Q$, for different explosives.
For most of the explosives examined, the rate of burning is a linear
function of the pressure. The rate of burning, at a given pressure,
increases smoothly with increasing Q, but it has been found that the
explosives examined fall into a number of classes. The evidence is
as follows (7, 8): at 50 atms if log $\dot{m}$ is plotted against Q we find
that:-

(a)   propyl, ethyl and methyl nitrates, mixtures of ethyl
      and propyl nitrates and ethyl and methyl nitrates
      diluted with hydrocarbons or alcohols lie on a straight
      line,

(b)   glycol (ethylene, propylene, butylene) dinitrates also
      lie on a straight line but for a given value of Q, the $\dot{m}$
      values are about half those in (a),

(c)   mixtures of nitroglycerine with triacetin lie on an
      intermediate line,

(d)   an ether link in the molecule leads to an increased rate
      of burning, e.g. D.E.G.N. compared with glycol dinitrates
      and $CH_3.O.CH_2.NO_2$ compared with the alkyl nitrates.

It is difficult to see why the rates of burning of methyl
nitrate, nitroglycerine and ethylene glycol dinitrate should differ
so much since the heats of explosion are approximately the same and
it is probable that, at high pressures, the rate controlling reaction
is the reduction of NO. At high combustion temperatures this
reaction probably proceeds by the homogeneous mechanism.

$$NO + NO \rightarrow N_2 + O_2$$

The homogeneous bimolecular decomposition of NO has a large energy
of activation (70 to 80 k. cals/mole) and, therefore, there may be
other routes for the reduction of NO at lower combustion temperatures.

From these facts and discussion it appears possible that the
rates of burning of the hotter organic nitrates at high pressures
depend only on the value of Q. This would explain the rather better
correlation of C with Q, on Scale I, than with $\dot{m} \times Q$. Secondly,

Confidential.

above 50 atms, the rate of burning of ethyl nitrate depends approximately on $\sqrt{P}$, and therefore the rate of burning of ethyl nitrate systems may not, at sufficiently high pressures, be appreciably different from those of compositions based on the dinitrate of butane 2:3 diol and, hence, the correlation of Q with $\dot{m} \times Q$ on Scale III might be better than that shown in Fig 1 if the rates of burning at high pressures were known.

2.3 Solid Explosives.

The sensitiveness of a pressed solid explosive depends markedly on the grain size and packing density and, of a cast explosive, on the crystal size. It is, therefore, not immediately obvious under what conditions comparisons of sensitiveness should be made. Qualitatively, however, the factor $\dot{m} \times Q$ does appear to give good correlation. Available results are shown in Table III.

TABLE III.

RATES OF BURNING OF SOLID EXPLOSIVES.

Compounds.	Rate of Burning. cm/sec.	g/sec. cm²	Density Pressure. g/cm³.	atms.	Q cals/g.	$\dot{m} \times Q$ cal/cm² sec.	Ref.
1. Mercury Fulminate.	1.55	5.9	3.80	1	400	2360	9
2. Trinitrotriazidobenzene.	0.62	1.05	1.70	1	1280	1350	9
3. Potassium Picrate.	1.50	2.75	1.83	1	459	-	9
4. Dinitrodinitrophenol.	2.15	?.?	1.45	1	-	-	9
5. Lead Styphnate.	explodes		3.07	1	880	>12000	9
6. 40% " " " + 60" talcum.	14.5	-	-	1	-	-	9
7. R.D.X.	36	58	1.60	1000	1250	73	10
8. P.E.T.N.	22	37	1.70	1000	1390	51	10
9. Tetryl.	8-9	13-14	1.57	1000	920	12-13	10
10. T.N.T. (cast).	13-14	22	1.60	1000	653	14.5	10
11. Nitroglycerine.	0.2	0.3	1.59	1	1466	440	2
12. Methyl Nitrate.	0.1	0.12	1.20	1	1450	175	2
13. Ethyl Nitrate.	0.008	0.009	?.10	1	754	7	2

Notes to Table III.

(1) $\dot{m} \times Q$ estimated at $P = 1$ atms. (linear extrapolation being used to obtain $\dot{m}$ where necessary).

(2) Q estimated as described previously; any metal assumed to be present in normal state.

(3) Only approximate figures of the densities of R.D.X., P.E.T.N.

Confidential.

Confidential.

and tetryl are quoted since the densities used are not given in Ref 10.

(4) Rates of Burning.

    (a) Below 1 atm pressure, rates of burning of trinitrotriazidobenzene and mercury fulminate depend linearly on the pressure (12); above 1 atm pressure there are no data.

    (b) The data on the solid high explosives may not be reliable since they were obtained from p/t records of the combustion of granular material. Further we find it difficult to accept that T.N.T. burns faster than tetryl since tetryl is "hotter" than T.N.T. and is a nitramine, and in general nitramines burn faster than nitrohydrocarbons (refs 4 and 7). The only other data, known to the authors, is that of Andrew (ref 13) quoted below.

DATA OF ANDREW.

COMPOUND	$\frac{m}{g/cm^2/sec.}$	CONDITIONS.
P.E.T.N.	0.055	130°C
R.D.X. (a)	0.057	100°C
Tetryl. (a)	0.15	133°C
m.N.T. (a)	0.017	room temp.
T.N.T. (b)	0.033	250°C

    (c) The rate of burning of nitroglycerine is also obtained from data of Andrew. Other data on nitroglycerine diluted with triacetin, obtained at E.R.D.E. suggest that the rate of burning of pure nitroglycerine is much nearer to that of methyl nitrate than the value given in Table III.

The sequence of the values of m x Q in Table III is:- initiators, nitroglycerine, methyl nitrate, (R.D.X., P.E.T.N.), (Tetryl, T.N.T.), and ethyl nitrate, which is in good agreement with the accepted sequence of sensitiveness and also with gap test results, e.g. T N.T. less sensitive than Tetryl (19) and T.N.T.< Tetryl< R.D.X.< P.E.T.N. (20). The small anomalies e.g. inversion of R.D.X. with P.E.T.N. and T.N.T. with tetryl may be due either to errors in measured rates of burning or non-linear dependence of rate of burning on pressure. The quantitative value of the scale is suspect in any case, because of the neglect of the mechanism whereby energy is transmitted to the explosive and converted into thermal energy and it seems unlikely that this is the same for liquids and crystalline solids.

Confidential.

In the absence of strictly quantitative data, we can conclude only that ṁ is an important factor in the sensitiveness of solid explosives, and not that ṁ x Q has a quantitative significance.

Before concluding this section, it should be pointed out that there is an upper limit to the rate of combustion. Compounds, whose "ideal" rate of burning is greater than this, will therefore, show no combustion regime on initiation (c.f. Bowden, Ref 15) but will give immediate detonation. Certain of the azides may show this behaviour. Further consideration of the matter is given in Appendix II.

2.4 Plastic Materials.

The plastic materials considered are Plastic Propellants, which consist of a crystalline oxidant, e.g. ammonium perchlorate, cemented with a binder such as polyisobutylene and a wetting agent, e.g. lecithin. Some gap test results, on Scale III, are given in Table IV.

The C values in Table IV are much smaller than would be expected from the value of ṁ x Q. Further, the presence of materials, e.g. Cr_2O_3, which catalyse the low pressure combustion process appears to have a slightly negative effect on the sensitiveness. This may be because the catalyst has no kinetic effect under the pressure conditions of the gap test and, therefore, reduces the rate of burning by lowering the value of Q. The effect of occluded air on the sensitiveness of plastic propellants is similar to that produced by air bubbles in liquids.

Two possible reasons why the C values should be unexpectedly low can be suggested. Firstly the pressure exponent of the rates of burning is about 0.7, i.e. less than unity and, therefore, the value of ṁ x Q under the pressure conditions of the shock wave would be very much less than if the pressure exponent were unity as it appears to be for many one phase systems. Secondly, the transmitted shock pressures in the explosive material depend on the physical properties of the latter and may be greater or smaller than the pressure of the incident shock. Relative to liquids, this would have the effect of displacing the card values for a given range of ṁ x Q either to larger or smaller values.

3. SIGNIFICANCE OF GAP TEST.

3.1 In an adiabatic system having perfect mechanical confinement any compound which decomposes exothermically will eventually explode. The times required for this to happen are, however, very long at ordinary temperatures. If, in such a system, a sufficiently large "hot spot" is formed then the resultant explosion will centre about this point. In practical systems the critical energy required to start an explosive event depends very much on the mechanical and thermal confinement. Let us now consider the gap test with these ideas in mind. In the gap test a strong shock or sequence of shocks

Confidential.

T A B L E IV.

GAP SENSITIVENESS (SCALE III) OF PLASTIC PROPELLANTS.

CODE NO. OF COMPOSITION. (See Appendix III)	Density	Rate of burning at 1000 p.s.i.		Q cal/g	ΔEQ cal/cm^2/sec	C	
		cm/sec	g/cm^2/sec			"Free" from air	Containing air
E202.	1.70	1.80	3.06	958	2931	16	-
E260.	1.67	1.50	2.51	865	2167	13	-
E261.	1.65	1.15	1.90	775	1591	10	-
E911 = (E202 + 5% Cr$_2$O$_3$)	1.73	2.25	3.89	931	3624	15	22
E912 = (E260 + 5% Cr$_2$O$_3$)	1.71	2.0	3.42	840	2873	12	20
E913 = (E261 + 5% Cr$_2$O$_3$)	1.69	1.70	2.87	751	2158	10	16
E937 = (E202 + 5% K$_2$Cr$_2$O$_7$)	1.71	1.45	2.45	790	2356	12	-
E938 = (E260 + 5% K$_2$Cr$_2$O$_7$)	1.68	1.19	2.00	860	1719	>10	-
E939 = (E261 + 5% K$_2$Cr$_2$O$_7$)	1.66	0.94	1.56	770	1202	>10	-
RD 2200	1.78	1.88	3.35	1140	3815	30	-
RD 2043	1.73	0.69	1.19	455	541	>10	-
RD 2331	1.60	0.30	0.48	499	240	>10	-
RD 2332	1.58	0.25	0.40	404	160	>10	10

(see Fig. 3) is transmitted to the explosive under examination, the explosive being contained in a standard vessel, a metal tube. The criterion of a positive effect, i.e. addition of energy from the explosive to the shock wave, on Scale I is the fragmentation of the container and, on Scale III, the tearing of a metal end-plate. The initiating shock is not sufficiently strong to cause such damage. This implies that to get a positive effect either a reactive shock, not necessarily a stable one, must be propagated through the explosive or there must be a rapid increase in pressure above that of the shock pressure transmitted to the explosive from the donor across the gap.

It is necessary at this stage to anticipate our conclusion in order to clarify discussion. In some way, the initiating shock starts an exothermic reaction at some point or points in the explosive. We shall regard this exothermic reaction as a combustion reaction and define this whole process as initiation. Under favourable conditions, i.e. a sufficiently high initiating pressure and adequate confinement, the pressure at the point or points of initiation will increase. This process we call growth. If the dimensions and confinement of the explosive are large enough, this

Confidential.

Confidential.

growth process will lead to the formation of a shock wave of suffic-
ient strength to initiate more explosive, i.e. a reactive shock will
be formed, and eventually a stable detonation wave may be produced.
We imagine, therefore, the sequence of events to be as follows:-
initiation→ growth→ reactive shock→detonation wave.

The growth process may be sufficiently vigorous to give a positive
effect in the test. In Scale I, the photographic evidence shows
that in diethylene glycol dinitrate a low velocity detonation wave is
propagated. The "positive effect" in Scale I is sufficiently large,
i.e. fragmentation of the container, to support the photographic
evidence that a detonation wave is produced. The "positive effect"
is much weaker in Scale III and it is impossible, at present to
state whether an explosive reaction or an unstable reactive shock is
produced.

A priori there is no reason to assume that ease of initiation
will run parallel with ease of growth as we pass from one explosive
to another. The two cases of particular interest are:-

(a) initiation easy, growth difficult,

(b) initiation difficult, growth easy.

In case (a), the explosive will have to be over-initiated in order
to get a positive effect in the test. In case (b), a shock pressure
sufficient to initiate the explosive, will produce a reactive shock
of sufficient strength to give a positive result. It does not
follow therefore, that the gap test necessarily measures the same
property for all explosives.

On an empirical basis it can be argued that the gap test
measures ease of propagation. Some sort of assessment of ease of
propagation can be made by examining the propagation of detonation
of explosives in tubes of differing dimensions. In a few cases
direct comparison with gap test results is possible. Such results
are given in Table V (details of the propagation test are given in
Appendix IV); the figures in the "Results" column give the minimum
tube diameter in which the explosive propagates detonation under
the conditions of test.

Explosive A propagates more readily than explosive B despite the
fact that it is less sensitive than B. In each pair the explosive
which propagates better has the higher value of Q. This limited
evidence suggests, that Scale III measures either ease of initiation
or "build-up" of an explosion wave (growth) rather than ease of
propagation.

In Scale I the initiating shock is weaker, the charge diameter
is smaller and the wall thickness of the metal container less than
in Scale III. It is also possible that the accepted indication of

Confidential.

T A B L E V.

COMPARISON OF PROPAGATION AND GAP TEST RESULTS.

	EXPLOSIVE.	GAP TEST SCALE III.	Q cal/g.	RESULTS OF PROPAGATION TEST.
A	N_2H, 54.2%. $N_2H_4NO_3$ 36.5%. H_2O 9.3%.	10	570	5/8"
B	Propyl Nitrate.	16	294	greater than 2".
A	Dithekite D13.	30	1265	less than 1/16".
B	Ethyl Nitrate.	43	754	1/4".
A	Nitromethane.	24	969	less than 1/4".
B	Ethyl Nitrate.	43	754	1/4".
A	Nitromethane.	24	969	less than 1/4".
B	60/40 EtONO$_2$/PrONO$_2$.	27	570	5/8".

a positive result, namely fragmentation of the containing tube, is
more rigorous than that required in Scale III. In reference to Fig.
2 it was pointed out that for a given value of $\dot{m}$ x Q, the explosive
with the higher value of Q was apparently the more sensitive. It
was shown in Section 2.2, however, that this effect may also be due
to uncertainty in the value assigned to the rate of burning, that
observed differences in rates of burning at low combustion pressures
may disappear at pressures of 10^3 or 10^4 atms. Another aspect of
the matter is shown in Fig. 4 where the explosives assessed on Scale
I are plotted on a grid of $\dot{m}$ x Q and $\rho_0 Q$, ρ_0 being the density of
the explosive. The explosives fall arbitrarily into two classes:-

$$\text{(a)} \quad c > 16. \qquad \text{and} \qquad \text{(b)} \quad c < 6.$$

and the field can be divided in such a way that the two classes are
separated. It appears, therefore, that a C value less than some
value between 6 and 16 on Scale I has no quantitative significance.
For a given value of $\dot{m}$ x Q, $\rho_0 Q$ must be above a certain value before
Scale I gives significant results. We shall assume therefore (see
argument in Section 6.2) that only explosives in which the growth of
the explosion centre is rapid can be assessed on Scale I; in other
words ease of initiation or of growth of the explosion centre is
measured if Q is large enough The factor $\rho_0 Q$ is larger for ethylene
glycol dinitrate/triacetin (65/35) than for butane 2:3 diol dinitrate
and thus may be the cause of the large apparent difference in
sensitiveness on Scale I.

3.2 The gap test technique was originally selected for this work
at E.R.D.E. because it was thought that, in principle, the strength
of the initiation shock could be measured. The properties of the
shock wave, which appear to be important, are its peak pressure,

Confidential.

velocity and thickness from which can be deduced the time for which any element of explosive is subjected to pressure. We have not yet obtained adequate photographs of the shock waves in liquids subjected to gap tests but the photographs so far obtained (Fig 3) show that there is a succession of shock waves. However, measurements of shock pressures have been made. The main difficulty in measurement is one of principle. If a shock wave passes from one medium to another, the shock pressure in the second medium may be higher or lower than the shock pressures in the first. For weak shocks the criterion is the acoustic impedance, i.e. product of velocity of sound (c) and the density (ρ). If the shock is travelling from a medium of low impedance (small ρc) into one of high impedance, the shock pressure in the second medium will be higher than in the first. It follows from this that measurement of the shock pressure by the methods described below may not give the pressure in all explosives since they differ so much amongst themselves in physical properties.

Pape (11) has measured the pressure in two ways:-

(a) by transmitting the shock to a Hopkinson bar, and

(b) by transmitting the shock to water and calculating the shock pressure from the measured velocity.

Both methods of measurement give about the same values for the pressure (see Fig. 5) although the form of the curve is rather unexpected in the case of water. The main point, however, is that the pressures are about the same despite the large difference in acoustic impedance between water and steel. It should be noted, however, that the Hopkinson bar result is a time averaged result (for the figures quoted below, the time interval is 5 μsecs), whereas that from the velocity in water is an instantaneous one for the leading shock wave (see Fig 3). However, the Hopkinson bar results are simple and are as follows:-

Scale I $\log_{10} P = - 0.0339\ C + 4.63.$
Scale III $\log_{10} P = - 0.0250\ C + 4.76.$

where P is measured in atms and C is the number of cards in the attenuating stack.

Measurements with fewer than 30 cards were not significant because permanent damage was done to the Hopkinson bar and above 50 cards the results were not reproducible. Extrapolation below 30 cards is probably permissible but not above 50 cards (gap test results are irreproducible at card values above 50).

The estimated minimum pressure required to obtain a positive result with Dithekite D13 on Scale III is about 1.0×10^4 atms and about 1.2×10^4 atms on Scale I. The only other cases for which a direct comparison is possible fall on that part of Scale I where the

Confidential.

results do not appear to have quantitative significance. If $\dot{m}$ is a
linear function of P and the pressures measured by the Hopkinson bar
are reliable, the value of $\dot{m}$ x Q at the initiation pressures for
explosives can be estimated. On Scale I (C $\geq$ 16) the value of $\dot{m}$ x Q
is about 5 x 10^4 cal/cm^2 sec and on Scale III about 3 x 10^4 cal/cm^2
sec. The scatter is quite large, as the results in Table VI show,
but nevertheless the rates of energy release required for initiation
on Scale I do appear to be significantly higher than those required
on Scale III. This is to be expected in view of the lighter
conditions of confinement in Scale I.

It has been mentioned previously that Plastic Propellants
(Table IV) are less sensitive than expected from the value of $\dot{m}$ x Q.
It was suggested that a reason for this might be that the pressure
exponent of the rate of burning is less than unity. Assuming that
the critical rate of energy release on Scale III is 3 x 10^4 cal/cm^2
sec (Table VI) then, $(\dot{m} \times Q)_1 / (\dot{m} \times Q)_2 = (P_1/P_2)^n$, where n is the
pressure exponent, subscript 1 refers to reference conditions (e.g.
50 atms for liquids, 1000 p.s.i. for plastic propellant) and
subscript 2 to the conditions in the initiating shock i.e. $(\dot{m} \times Q)_2$ is
3 x 10^4 cal/cm^2 sec and P_2 can be calculated from the value of C.
The above equation for Plastic Propellant can be written: $(\dot{m} \times Q)_1 /$
$3 \times 10^4 = (68/P_2)^n$. Values of n have been calculated for the
compositions XD 2200, B 202, B 260, and B 261 (Table IV), i.e. for
compositions containing no combustion catalysts. The values are
0.41, 0.40, 0.44, and 0.50 respectively. Although less than n deter-
mined at low pressures (1000 p.s.i.) such values are not unreasonable
and, therefore, the low sensitiveness of Plastic Propellants may
be ascribed to their combustion properties and not to their physical
properties.

3.5 It can be concluded from this discussion that the gap test does
not measure ease of propagation of detonation but ease of initiation
and/or the growth factor. It appears that at least a low-order
detonation is produced under the conditions of Scale I but it has
not been proved whether a positive result on gap test Scale III
involves a low-order detonation, i.e. the rate of growth under the
conditions of Scale III may not be sufficient to set up a reactive
shock.

4. RIFLE BULLET SENSITIVENESS.

4.1 Liquid Explosives.

It was shown in Ref 4 that the sensitiveness of liquid explosives
to rifle bullet attack, under the conditions specified in Ref 14,
could be correlated with the sensitiveness on gap test (Scale III).
An explosion, or partial or complete detonation, was accepted as a
criterion. It is possible, however, that an explosion cannot always
be regarded as an incipient detonation since it might be argued that
the bullet created a large surface in the liquid, e.g. by cavitation,
which ignited and gave rise to explosive combustion. This could

Confidential.

T A B L E VI.

ESTIMATED RATES OF ENERGY RELEASE FOR INITIATION OF EXPLOSION.

SCALE I.				SCALE II.			
EXPLOSIVE.	C	RATE OF ENERGY RELEASE cal/cm^{2}sec		EXPLOSIVE.		C	RATE OF ENERGY RELEASE cal/cm^{2}sec
N.G.	T.A.			Ethyl Nitrate.		45	3.0×10^4
85	15	47	2.4×10^4	ETONO$_2$/EtOH			
80	20	26	7.1×10^4	(90.4/9.6)		28	2.9×10^4
75	25	22	5.4×10^4	ETONO$_2$/PrONO$_2$			
E.G.N.	T.A.			(60/40)		27	3.3×10^4
84	16	29	6.1×10^4	Propyl Nitrate.		16	2.0×10^4
80	20	27	4.6×10^4	Nitromethane.		24	3.1×10^4
75	25	21	4.4×10^4	Butane 2:3 dinitrate			
Dithekite D13			(3.9×10^4)	+ 4% ETOH.		40	1.6×10^4
D.E.G.N.		27	8.9×10^4	60% N.G. +			
				40% Triacetin.		16	2.9×10^4

NOTE: ♦ T.A. - Triacetin, N.C. - Nitroglycerine, E.G.N. - Ethylene Glycol Dinitrate.

---

produce a sufficiently rapid rise in pressure to cause severe damage to the container without the onset of detonation. We have, therefore, re-examined the results from Ref 14 although the data are statistically inadequate. Significant results a.? shown in Table VII.

Apart from anomalies, being within the scatter expected of such a small number of trials, we see that there is a broad correlation with gap test sensitiveness whichever criterion is regarded as a positive event.

4.2 Solid Explosives.

We have as yet very few data on solids suitable for comparison with the liquid explosives and gap sensitiveness measurements. The available results are given in Table VIII.

The definition of explosion, used in this work, is:- "Impact accompanied by a flash or slight report. Box split along seams and sometimes thrown as much as 15 yards." (Ref 14). Such an event could easily be produced by vigorous burning inside the box and it is hardly surprising that materials, such as Plastic Propellants, should

TABLE VII.

SENSITIVENESS OF LIQUID EXPLOSIVES TO RIFLE BULLET ATTACK.

EXPLOSIVE.	NO. OF TRIALS	PERCENTAGE DETON-ATIONS	DETONA-TIONS & EXPLOSIONS	C SCALE III
EtONO$_2$	29	55	55	43
EtONO$_2$/PrONO$_2$, 80/20.	15	13	13	37
EtONO$_2$/ Nitromixture, 80/20.	25	24	28	35
EtONO$_2$/Nitromixture, 75/25.	12	50	50	33
EtONO$_2$/PrONO$_2$, 70/30.	30	10	10	31
EtONO$_2$/Nitromethane, 60/40.	29	10	21	31
EtONO$_2$/PrONO$_2$, 50/50.	30	7	13	30
Dithekite D 13.	60	8	9	30
EtONO$_2$/Nitromethane, 40/50.	17	6	6	29
EtONO$_2$/Nitromethane, 70/30.	30	0	7	29
EtONO$_2$/Nitromethane, 60/40.	30	0	0	27
EtONO$_2$/PrONO$_2$, 60/40.	74	1	3	27
Nitromethane.	30	0	0	24
Dithekite D 20.	60	0	0	19
PrONO$_2$.	30	0	0	16

TABLE VIII.

SENSITIVENESS OF SOLID EXPLOSIVES TO RIFLE BULLET ATTACK (REF.14).

EXPLOSIVE.	DENSITY g/cm^3	C SCALE I	SCALE III	NO. OF TRIALS	PERCENTAGE. DETONA-TIONS	EXPLO-SIONS
Amatol. (80/20).	1.3	25	–	30	7	20
RDX/BWX. (90/10), Pressed.	?	23	–	29	0	10
RDX (Pressed).	?	–	–	27	81	19
TNT (Pressed).	?	24	–	30	0	40
ED 2200)	1.78	–	30	30	0	90
ED 2201) Plastic	–	–	–	30	0	27
K 202) Propellants.	1.70	–	16	30	0	67
ED 2043)	1.73	–	10	30	0	23

Confidential.

give explosions (so defined) under rifle bullet attack since they
have much higher rates of burning than liquid explosives at low
pressures (compare Table I and Table IV). These results, and the
known rates of burning of liquid explosives and Plastic Propellants,
suggest that the rifle bullet starts a combustion reaction at a
relatively low pressure.

When we consider the few results with pressed solid granular
explosives, there is no correlation with liquid explosives. Liquid
explosives having C values greater than 20 on Scale I would certainly
give rise to a large percentage of detonations in the rifle bullet
test. A liquid explosive with a C value of 25 on Scale I would have
$\dot{m} \times Q$ (at 50 atms. pressure) equal to about 500 cal/cm²sec. We
estimate that the rate of burning of an homogeneous mixture of RDX
and Beeswax (90/10) would be about 1.5 g/cm²sec at 50 atms. since
its heat of explosion is about 800 cal/g (c.f. Fig 7 of Ref 7), which
leads to a value of 1200 cal/cm²sec. for $\dot{m} \times Q$. The explanation of
the discrepancy may stem from the fact that the explosive is
inhomogeneous. The same conclusion might be drawn from the relative
sensitivenesses of RDX/TNT and T.N.T., i.e. RDX/TNT behaves more
nearly like T.N.T. than R.D.X. The effect of inhomogenelty on
sensitiveness is discussed later. Other factors not considered ..
grain size, crystal size and loading density, all of which have an
effect on sensitiveness.

5. SENSITIVENESS OF PRESSED CHARGES OF T.N.T.

One of the difficulties in sensitiveness work is to obtain a
logical link between the sensitiveness of liquid and solid explosives.
Certain explosives, however, are stable in the liquid and solid state.
The easiest one to handle is T.N.T.; another is Picric Acid. In
these systems it is possible to compare the sensitiveness of a liquid
and a solid, for which the chemical nature of the decomposition
process is the same, the only difference being the final temperatures
of the decomposition process which depends on the magnitude of the
latent heat of fusion.

It was decided to determine the sensitiveness of T.N.T. under
the following conditions:- (a) as a liquid at 90°C, (b) as a cast
solid at ambient temperature, and (c) as a pressed charge in which
the loading density, the grain size and the crystal size were varied.
Some results obtained at this establishment are shown in Figs. 6a
and 6b. These were obtained on gap Scale II which is almost the same
as Scale I, except for a difference in the mechanical properties
of the steel of the containing tube.

The main conclusions are:-

(a)   the sensitiveness is a function of density, increasing
      with density, passing through a maximum and then decreasing

Confidential.

Confidential.

(b) at specified density, pressed charges of large grain size are more sensitive than ones with small grain size,

(c) a pressed charge of grains made from large crystals is less sensitive than one of grains made from small crystals.

The results with cast T.N.T. and liquid T.N.T. are shown in Table IX.

TABLE IX.

SENSITIVENESS OF T. N. T.

FORM OF T.N.T.	SCALE I.	SCALE II.	SCALE III.
Normal brown, (cast).	7	12	30
Liquid at 90.	-	15	30

The agreement between the sensitiveness of liquid and cast T.N.T. is thought to be fortuitous because it is well-known that the sensitiveness of cast T.N.T. can be altered appreciably by variation of the crystal size. This matter is discussed in Section 6.

6. ANALYSIS OF RESULTS.

6.1 Before attempting to analyse the main results, we may summarise them briefly:

(a) the product $\dot{m} \times Q$ (at $P = 50$ atms.) gives a good correlation of the sensitiveness of liquid explosives on gap test Scale III and by the rifle bullet test.

(b) generally speaking the product $\dot{m} \times Q$ gives a good correlation qualitatively with sensitiveness over the whole field of explosives.

(c) on gap test Scale I the product $\dot{m} \times Q$ is not a sufficient criterion, the magnitude of Q or ρQ also appears to be important.

(d) there are some anomalies amongst the solid explosives, e.g. R.D.X. which despite a higher value of $\dot{m} \times Q$, is less sensitive than P.E.T.N. (20) and RDX/BWX is less sensitive on Scale I than would be guessed from its estimated rate of burning (if it were homogeneous).

(e) the rifle bullet sensitiveness of amatol, pressed T.N.T. and pressed RDX/TNT is less than that for liquids of similar

Confidential.

gap test sensitiveness.

6.2 Growth of an Explosion Centre.

We assume that mechanical action produces a localised high temperature in the explosive. This high temperature can be produced by friction, by shock waves or by local stress concentration or release. We assume, furthermore, that a combustion reaction starts at the hot spots. This process we define as "initiation", and from Bowden's work (15) it would appear generally true. In certain cases, (e.g. certain initiators), it may not be true and the probable reason for this is discussed in Appendix 2. In order to get a measurable explosive effect it is necessary for the combustion reaction to lead to an increasing pressure. Since this also requires an increasing size of the "hot spot", we define this second stage as growth. The rate of increase of pressure in an "explosion centre" of radius r is given by equation 10 of Appendix V:-

$$\frac{dP}{dt} = \frac{3P}{r}\left[\frac{S}{M}\cdot\frac{R_b \rho_c Q'}{c} - \gamma\left\{\frac{R_b}{r} + A\right\}\right] \qquad 1$$

If R_b is a linear function of pressure, the factor

$$\frac{M_b \rho_c Q'}{c P} = \frac{R_b \rho_c Q'}{c}$$

is approximately independent of pressure (ρ_c will increase slowly with pressure). Neglecting changes in M and c with pressure, we can write equation 1 in the form

$$\frac{dP}{dt} = \frac{3P}{r}\left[K R_b \rho_c Q' - \gamma\left\{\frac{PR_b}{r} + A\right\}\right] \qquad 1a$$

$$= \frac{3PR_b}{r}\left[K\rho_c Q' - \frac{\gamma}{r} - \frac{\gamma A}{R_b}\right] \qquad 1b$$

At a given pressure P, a large value of dP/dt is favoured by large values of R_{bo} and $\rho_o Q'$ i.e. by large values of $R_{bo}\rho_o Q'$ which is approximately proportional to $\dot{m} \times Q$ (at any reference pressure), and $\rho_o Q'$.

If we put $S = R_{bo}\rho_o Q'$ equation 1b can be written

$$\frac{dP}{dt} = \frac{3P}{r}\left[KS - \frac{PS}{R_b r} - \gamma A\right] \qquad 1c$$

i.e. for a given value of S, dP/dt increases with increasing values of $\rho_o Q'$.

If, therefore, initiation is relatively easy and we are using a sensitiveness test in which growth must occur to give a measurable effect, as in gap tests, we should expect sensitiveness to increase with increasing values of S, approximately proportional to $\dot{m} \times Q$, and of $\rho_o Q'$. This is, in fact, what we have found with explosives on Scales I and III (see Figs 1, 2 and 4).

If $R_b = R_{bo} P^n$, where n < 1, we should expect the material to be less sensitive than would correspond to the value of $\dot{m} \times Q$ at the reference pressure of 50 atms. This appears to be the case with plastic propellants (section 2.4) and hydrazine and hydrogen peroxide (discussed in Ref 4), all of which materials have values of n less

Confidential.

Confidential.

than unity.

6.3 Initiation by Cavity Initiation.

A pressed granular explosive must contain gas-filled cavities. It is possible that initiation of detonation of such explosives is produced by the adiabatic compression of the gas in the cavity. The pressure required to initiate a combustion reaction in an explosive material containing cavities is (equation 5, Appendix VI):-

$$\log d + \tfrac{1}{3}\log\left\{\frac{\delta_o - \delta}{\delta}\right\} = \log D - B\log P_c$$

where d is the grain size, δ is the density and P_c is the initiating pressure. Accordingly, the pressure required for initiation decreases as the grain size is increased (at constant density). With a fixed grain size, the initiating pressure decreases as density is reduced.

Thus, if initiation is the controlling factor and not growth, (defined in Section 6.2), the sensitiveness of pressed charges of explosive will increase with increasing grain sizes and decrease density. Clearly the sensitiveness cannot increase indefinitely with decreasing density because:-

(a) at some limiting low density the particles of explosive will only just be in contact, and

(b) ease of initiation increases with increasing value of d (equation 2) but rate of growth decreases with increasing value of d, i.e. at some density, which will be lower the smaller the value of d, the pressure required for a sufficiently rapid growth will be larger than that required for initiation and hence will become the controlling factor.

If compression of a pressed porous solid is primarily the "compression" of the cavities, the r in equation 1 is the radius of the cavity when compressed. The initial radius of the cavities is

$$\frac{d_o}{2} = \frac{d}{2}\left\{\frac{\delta_o - \delta}{\delta}\right\}^{1/3}$$

(Equation 4, Appendix VI)

where d_c is the diameter of the cavities. Now for adiabatic compression of the cavity

$$\ln(P_i/P_o) = -3\gamma\ln(r_i/r_o) = -3\gamma\ln(2r_i/d_o)$$

where i refers to initial conditions (before compression) and o to initiating conditions. Hence

$$r_o = \frac{d_o}{2}\left\{\frac{P_i}{P_o}\right\}^{1/3\gamma} = \frac{d}{2}\left\{\frac{\delta_o - \delta}{\delta}\right\}^{1/3}\left\{\frac{P_i}{P_o}\right\}^{1/3\gamma}$$

3

In Appendix V it was shown that A in equation 1, which is a measure of the confinement conditions can be written (at the beginning of growth)

$$A = \frac{E}{\omega\gamma}\cdot\frac{1}{n+1} = \frac{E}{\delta}\cdot d\cdot\delta_o\cdot\left\{\frac{\delta}{\delta_o - \delta}\right\}^{2/3}\left\{\frac{P_i}{P_o}\right\}^{-2/3\gamma}$$

4

Confidential.

Confidential.

Combining equations 3 and 4 with equation 1 we obtain for the initial rate of growth

$$\frac{dP}{dt}\Big|_{i_0} = \frac{b}{a} \cdot \left\{\frac{\delta}{\delta_0 - \delta}\right\}^{\frac{1}{3}} P_0^{\frac{1}{3}} \left[K S - \frac{P_0 S}{\rho_0 \sigma^2}\right] - \gamma E \cdot \frac{I_0}{\delta_0 - \delta} \cdot P_0^{\frac{1}{3}}$$ 5

when $P_4 = 1$ atm.

We can see from equation 5 that $(dP/dt)_{i_0}$ decreases with decreasing pressure and decreasing density. This effect of changes in bulk density on the two terms on the R.H.S. is different, but not enormously so, as shown in Table L.

TABLE L

$\delta_0 = 1.55$ (as in cast T.N.T.)

δ	$\delta/(\delta_0-\delta)$	$[\delta/(\delta_0-\delta)]^{\frac{1}{3}}$	Ratio of Factors.
1.4	10.3	2.15	4.7
1.2	4.4	1.5	2.9
1.0	2.7	1.2	2.3
0.8	2.1	1.02	2.1
0.6	1.6	0.86	1.9

Thus at densities of 1.0 g/cm^3 or less the ratio of $[\delta/(\delta_0-\delta)]^{\frac{1}{3}}$ and $\delta/(\delta_0-\delta)$ does not depend much on δ i.e. the relative importance of the confinement factor does not depend markedly on δ. We have, therefore, the following picture. At values of δ/δ_0 near to unity (not too close to unity, since the confinement term containing A approaches infinity faster than the first term) initiation may be difficult and growth relatively easy. As δ decreases, initiation becomes easier and growth more difficult. At some δ, the minimum pressure required for initiation may be too low to produce a fast enough rate of growth, i.e. a higher initiating shock pressure will be necessary to get growth fast enough to produce explosive combustion or a reactive shock. The density at which the change over occurs will be lower the smaller the value of δ.

6.4 Pressed Charges of Explosive.

The behaviour of charges of pressed T.N.T. (Section 5 and Fig 6) approximates to the description in Section 6.3. It is worthwhile inserting numerical values into equation 2 in order to determine whether the theoretical initiating pressure is of the same order as our estimate from other experimental work. In equation 2 we have (Appendix VI).

$$D = \frac{b \cdot B}{a \cdot c} \cdot P^{-1/3\gamma} = \frac{680}{\rho_0 c} \cdot \frac{A}{c} \cdot \frac{I_0}{\tau_m} \qquad (P_i = 1 \text{ atm.})$$

3. This is somewhat less than the heat of explosion (Ref 2). The

Confidential.

measured value of the heat of explosion is about 1000 cal/gm (Ref 16) and the minimum estimate is 653 cals/gm (Table III). We shall assume a value of 700 cal/gm.

m. Since $\dot{m}/\dot{m}$ is approximately independent of pressure (if $\dot{m}$ depends linearly on pressure) we can use the value of $p/\dot{m}$ at one atmosphere pressure.

According to Andreev (Ref 13), $\dot{m}$ (1 atm.) = 0.017 gm/cm^2 sec. By linear extrapolation from the value at 1000 atms, we obtain $\dot{m}$ (1 atm.) = 0.022 g/cm^2 cm. Although this agreement is satisfactory, we find difficulty in accepting this value because

(a) it is higher than that for an alkyl nitrate of the same heat of explosion (Fig 7 of Ref 7), and,

(b) the value of $\dot{m} \times Q$ (at 50 atms), deduced from the sensitiveness on Scale III corresponds to a value of $\dot{m}$ (1 atm.) of about 0.005 g/cm^2 sec. which appears more reasonable on our experience of the rates of burning of different classes of chemical compounds (Ref 7).

For the other physical properties we shall assume:- $\bar{\rho}$ = 0.002 g/cm^3, γ = 10^{-3} g/cm sec., Ω = 25, and R = 82 cm^3 atm/deg.g. With these values we obtain D = 3.4 ($\dot{m}$ = 0.02 g/cm^2sec) and D = 16.3 ($\dot{m}$ = 0.005 g/cm^2sec). Equation 2 then becomes

$$\log d + \gamma. \log[(\delta - \delta)/\delta] = \log(3.4 \text{ or } 16.3) - B \log P_o$$ 6

$B = (3\gamma - 1)/3\gamma$. If γ = 1, B = 0.67; if γ is large, B approaches unity. We shall choose therefore γ = 1.4 and B = 0.75. Further since the charges were made from cast T.N.T. we shall assume δ_e = 1.55 instead of 1.65, the crystal density.

Evaluating P_o, with δ = 1.0 g/cm^3 and d = 0.01 cm, we obtain a value of log P_o between 3.5 and 4.5 i.e. P is between 3 x 10^3 and 3 x 10^4 atms. Now on Scale II the values of C lie approximately between 20 ± 5. Scale II is very similar to Scale I, the pressures probably being somewhat higher on Scale II for a given card value. From the formulae in Section 3.2 we find that log P varies from about 3.80 to 4.10, which is within the limits of the calculated pressure.

For a given grain size, the sensitiveness increases by an amount corresponding to 5 cards or less as the density changes from 1.3 g/cm^3 to 0.8 g/cm^3. Equation 2 should give a value which is not less than this since there must be a change over from the control by initiation to control by growth of explosion centres. We have, therefore,

$$\gamma. \log[(\delta_o - \delta_1)/\delta_1].[\delta_2/(\delta_o - \delta_2)] = B \log(P_2/P_1)$$

With the above values of δ_1 and δ_2 and δ_o = 1.55 we obtain log P_2/P_1 = 0.35 which corresponds to a difference in C (i.e. $C_1 - C_2$) of about 10 cards. This is reasonable agreement in view of the complications due to the growth of the explosion centres.

Confidential.

We have shown that changes in d and δ affect the initiation and growth factors in opposite senses. It follows from this that equation 2 will always overestimate the effect of changes in d and δ on the initiation pressure P_o. On Scale II a pressed charge ($\delta = 1.05$ gm/cm³) with grain size between 20 and 36 B.S.S. has a C value of 25. A pressed charge at the same density with grains passing 200 B.S.S. has a C value of 21. A grain size of 20 to 36 B.S.S. size has a mean diameter of about 600 microns; grains passing 200 B.S.S. have a diameter less than 76 microns. Thus a change in d by a factor of 10 changes the C value by 4 cards, corresponding to a change in log P of about 0.14. Now according to equation 6 a change of d by a factor 10 will change log P by 1.33 (corresponding to change in C of about 40 cards). The discrepancy is enormous. Let us, however, consider the effect of change of grain size on the rate of growth of an explosion centre. Neglecting all terms except the first in equation 5 we have, assuming $P_i = 1$ atm,

$$\left.\frac{dP}{dt}\right|_o = \frac{b}{I} \cdot \left\{\frac{z}{\delta - \delta}\right\}^{\frac{2}{3}} \cdot P_o^{(3\gamma+1)/3\gamma} \cdot W_2$$

Assume that a pressure, P_o, is required to initiate a charge with grain size d. The pressure required to initiate a pressed charge with grains of 10d is (from equation 6) about $P_o/20$. The initial value of dP/dt for a grain size of 10d, is thus $0.1 \times (1/20)^{4/3} = 0.0025$ of the value for d. Thus the rate of growth of explosion centres is 400 times slower and if this rate is less than some critical value, a higher value of the pressure will be necessary, i.e. the decrease in initiating pressure will not be as great as that calculated from equation 6.

While this effect may well occur, the effect of changes in d is, according to equations 5 and 6, independent of δ. Now from Fig 6 we can see that a change of d by a factor 10 never has the marked effect calculated from equations 5 and 6. Therefore we conclude that

(a) our model is incorrect, or,

(b) our estimate of the size of the cavities is incorrect, or,

(c) a significant factor has been omitted from our model.

We do not believe that our model is basically incorrect because it leads to case of initiation increasing with increase in particle size whereas one based on growth as the controlling mechanism would give the opposite result. While the method of estimating the size of the cavity from d and δ is crude, we do not believe that a change of d by a factor of 10 can have as little effect as suggested by the experimental results unless some factor has been omitted.

One factor, has certainly been omitted. In Ref 2 it was shown that initiation occurred at a time τ after the arrival of the pressure wave, where τ is given by $\tau \sim 10/v^2 P$. Here v is the equivalent vapour phase rate of burning of the condensed phase, i.e. the vapour phase

rate of burning of the vapour at such an initial temperature that the final combustion temperature is the same as that for the combustion of the condensed phase. If the mass rate of burning depends linearly on P, v is independent of pressure. We have already estimated that m (1 atm.) for T.N.T. probably lies between 0.02 and 0.005 g/cm^2 sec. v therefore, lies between 2 and 0.5 cm/sec. i.e. v lies between $2.5/P$ and $40/P$. The pressures which we are considering are about 10^4 atm. Therefore the pressure pulse must have a duration between 2.5×10^{-4} and 4×10^{-5} secs.

In the gap test the pressure pulse is produced by attenuating the shock issuing from a tetryl charge. However, we know experimentally that a series of shock waves, rather than a single shock, is transmitted through the explosive. The reason for this has been suggested to us by Professor D. Pack. (Royal Technical College, Glasgow). After the tetryl pellet has detonated, the system consists of the detonation products, the attenuating card stack and the receptor explosive charge. A shock wave is transmitted through the card stack, part of which is transmitted as a shock wave into the explosive - part reflected. The reflected part is again reflected by the hot gases through the card stack towards the explosive. The explosive is thus subjected to a series of shocks; the shock pressures will clearly be larger and the pulse frequency shorter, the thinner the attenuating card stack. We deduce from this that the "effective" pressure may well be of shorter duration when the card stack is thick, i.e. the shock pressure is low. For cavity initiation this is the converse of the requirements for initiation.

Thus, as the grain size is increased, the pressure required for initiation decreases but the time during which this must act increases. We have shown, however, that the "effective" duration of the pressure pulse probably decreases with decreasing pressures in the gap test. If this is so, we can suggest an explanation of the discrepancy between the effect of changing d on the gap sensitiveness and that calculated by equation 2. As d increases, the pressure required decreases but the time during which this must act increases. In order to comply with this time requirement the initiation pressure must, therefore, at some value of d stop falling and start to increase. This is what is observed experimentally and explains why equation 2 must, at least with some explosives, grossly overestimate the effective of changing d on the initiating pressure.

6.5 Cast Charges.

Cast T.N.T. has a density of 1.55 g/cm^3 whereas the crystal density is about 1.64 at normal room temperature. The solid thus contains a large proportion of free space. If the cast solid crystal consisted of one large crystal, the gas (air) would be in a solution and uniformly distributed throughout the solid. If the crystal has localised imperfections and/or the charge consists of many crystals, the gas will diffuse and collect between crystal faces and at

crystal imperfections if sufficiently large. It is impossible to make an estimate of the size of pockets of gas, except that in cast charges they should be small since the only gas present is the air originally in solution and that produced by thermal decomposition. We can, however, be certain that the number of such cavities per unit volume whether between crystal faces or at crystal imperfections, will be larger the smaller the crystals. The crystal size is controlled by the rate of cooling. The more rapid the cooling, the smaller the crystals, the greater the number of imperfections and the smaller the amount of dissolved gas that diffuses away. If the attraction of the dissolved gas molecules for each other is greater than the attraction between them and the explosive, there will be a tendency for the dissolved gas to form microscopic imperfections (bubbles).

Let us, therefore, consider the cast solid of density δ with n cavities (pockets of gas) of radius r_1 per unit volume. We have

$$n \cdot \tfrac{4\pi}{3} \cdot r_1^3 = \frac{\delta_o - \delta}{\delta} \qquad \text{or} \qquad 4\pi n r_1^2 = \frac{3}{r_1} \cdot \frac{\delta_o - \delta}{\delta} \qquad 7$$

The confinement factor, A, in equation 1, depends on n and r_1. If r_o is the value of r_1 at pressure P_o, then

$$A = \frac{E}{4\pi} \cdot \frac{1}{n r_1^3} = \frac{E}{3} \cdot n \cdot \frac{\delta_o}{\delta_o - \delta} \left\{ \frac{P}{\pi} \right\}^{2/3\gamma} \qquad 7a$$

which is similar to equation 4. The growth equation (using equations 7 and 7a) is

$$\frac{dr}{dt}\Big|_o = \pi \left\{ \frac{4\pi n}{3} \right\}^{1/3} \left\{ \frac{\delta_o}{\delta_o - \delta} \right\}^{1/3} r_o^{1/3\gamma} \left[KS - \frac{\bar{P}S}{\rho_o C_p} \right] - \gamma E \frac{\delta_o}{\delta_o - \delta} r_o^{-(3\gamma-1)/3\gamma} \qquad 8$$

when $P_1 = 1$ atm.

The initiation equation, from equation 2 of Appendix VI and equation 7 above is

$$\log n - \log \frac{\delta_o - \delta}{\delta_o} = 3B \log P_n - 3 \log \frac{P_n}{\pi} - \log \frac{4\pi}{3} \qquad 9$$

As we pass from a microcrystalline casting to a single large crystal the density will approach nearer to δ_o, which in this case is the crystal density and n must approach zero but $[\log n - \log (\delta_o - \delta/\delta_o)]$ from equation 9, approaches infinity. Thus, on this model, a pure crystal should be insensitive. If we consider a cast explosive consisting of only a few crystals, we cannot define a mean density and therefore δ will have no meaning but the number of cavities will be few. If they are small initiation may be difficult but it will be easier than in the pure crystal; growth will be favoured by the smallness of the cavity. The net result will be an increase in sensitiveness but a reproducible sensitiveness will be obtained only with large charges if the crystals are large. As the crystal size decreases, n becomes the main factor since changes in δ only have a large effect when $\delta_o - \delta$ approaches zero. Thus initiation becomes more difficult but growth easier, not only because n increases but because P_n, the pressure required to produce initiation also increases. We should, therefore, expect initiation to be the controlling factor at some value of δ which will be closer to δ_o, the

Confidential.

smaller the crystal size. Microcrystalline charges should therefore behave like pressed charges.
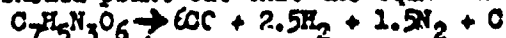
When a pressed charge of T.N.T. is made from grains obtained from a microcrystalline cast charge it is more sensitive than one made from grains from a cast charge with large crystals. (Figs. 6a and 6b). Now our model assumes that initiation occurs in the cavities between the grains. Any cavities inside the grains must be smaller than the cavities between the grains except possibly when $\delta \sim \xi$, therefore, it seems inevitable that initiation must occur outside the grains. If initiation occurs, the pressure must momentarily increase and the increase may be sufficient to set off "cavities" in the grains. This explanation is not entirely acceptable because it suggests that growth and not initiation is the controlling process, whereas the dependence on δ suggests the converse. The effect is, however, a small one and it may be that we are attempting to make too fine distinctions on a crude theory.

It is impossible to decide whether the controlling process in the sensitiveness of cast T.N.T. (normal brown) is initiation or growth. According to equations 8 and 9, if n decreases, initiation becomes easier and growth more difficult. Comparing a cast material with a pressed material made from particles of the cast material, we should expect n to be smaller for the cast material, i.e. initiation should be easier at a given density and growth more difficult. By extrapolation of the results in Fig 6 we see that the sensitiveness of cast T.N.T. appears to be about the same as that of a pressed composition of the same density. It is possible, therefore, but by no means certain, that growth is the controlling factor in cast (normal brown) T.N.T.

6.7 Liquid T.N.T.

Liquid T.N.T. (at 90°C) has a C value of 30 on Scale LI, i.e. the corresponding value of $\dot{m} \times Q$ at 50 atms. is about 150 cal/cm²sec. We have already pointed out that there are two possible values of $\dot{m}$ at 1 atm. viz 0.017 and 0.022 g/cm²sec. Taking a mean value of 0.02 g/cm²sec at 1 atm. pressure, we obtain 1.0 gm/cm²sec. at 50 atms. The value of Q is uncertain. Assuming that all the oxygen is present as CO in the combustion products, Q = 653 cal/gm. However, the experimental value for Q is about 1000 cal/g. The value of $\dot{m} \times Q$ (at 50 atms.) thus lies between 653 and 1000 cal/cm²sec. This does not correspond

FOOTNOTE: We should point out that the equation
$$C_7H_5N_3O_6 \rightarrow 6CO + 2.5H_2 + 1.5N_2 + C$$
which gives Q = 653 cal/gm is a most unlikely reaction. This value of Q is much lower than the experimental figure. Such a large uncertainty is not found with other explosives examined, except propyl nitrate. In combustion reactions, Q for propyl nitrate is undoubtedly larger than 396 cal/gm but even if it were as high as 400 cal/gm, (since $\dot{m} \times Q$ (at 50 atms.) would increase only from 34 to 46 cals/gm) it would not affect the correlation shown in Fig 1.

with the sensitiveness on either Scale II or Scale III and we find it difficult to accept such a high rate of burning from our knowledge of the combustion of explosives (ref 7). If we accept a value of $\dot{m} \times Q$ (at 50 atms.) of 150 cal/cm²sec, then $\dot{m}$ is 0.15 or 0.23 g/cm² sec depending on the value of Q. From Table IX we can estimate that liquid T.N.T. would have a value of about 12 on Scale I. Now $\rho_0 Q$ must lie between about 950 or 1500 cal/cm ($\text{since } \rho_0 = 1.46$ g/cm³). If we accept that $\dot{m} \times Q = 150$ cal/cm²sec, then Q must be not less than about 950 cal/g for the Scale I result to be comparable with Fig 4.

By analogy with other liquid explosives we assume that growth is the controlling factor in the gap test sensitiveness. We have seen that it is impossible to determine whether the controlling factor in the case of cast T.N.T. is initiation or growth. The pressure corresponding to C = 30 on Scale III is about 1×10^4 atms; that corresponding to C = 9 on Scale I is about twice as large. This is consistent with growth rather than initiation being the controlling factor, since the confinement on Scale I is less than that on Scale III.

In the growth process the number of cavities, n, the radius of the cavities r and the value of $\dot{m} \times Q$ are the important parameters. We can be certain that $\dot{m} \times Q$ will be larger for liquid T.N.T. than for cast T.N.T. since both $\dot{m}$ and Q are larger. However, we should not expect $\dot{m}$ to be larger than by a factor of two (see Andreew's values in Section 2.3). It is difficult to see what the nature of the cavities in the liquid could be (assuming they exist) but it is certain that they must be smaller in size and in number than those in a cast solid. It is, therefore, impossible to say whether a liquid should be more sensitive than a cast solid since although larger $\dot{m} \times Q$ and smaller r favour growth, the smaller value of n does not. Anticipating the conclusion from our discussion, that the mechanism of initiation in the gap test applied to liquid explosives is different from that for solid explosives, we must conclude that, even if growth is the controlling factor for both cast and liquid T.N.T., the fact that these have the same sensitiveness is a coincidence and not an instance of a general phenomenon.

This conclusion is confirmed by results with Picric Acid (Fig 7). Liquid Picric Acid at 120°C has a C value on Scale II of 54 compared with C values for pressed charges of Picric Acid which are not greater than 27.

These data are not quite conclusive since the gap test sensitiveness might have a temperature coefficient. The limited evidence available indicates that any such temperature coefficient is small. Thus the gap sensitiveness of liquid propyl nitrate is not more than one card different at -15°C from the value at about +15°C. Similarly the sensitiveness of nitroguanidine changes by one card when the temperature is increased from 15°C to 95°C. (22).

Confidential.

6.8 R.D.X/B.W.X.

In Section 4.2 we have suggested that the sensitiveness of pressed RDX/BWX is less than would correspond to the growth factor $h \times Q$ if it were homogenous. In general, whether initiation or growth were the controlling factor we should expect R.D.X. systems to be more sensitive than other solid explosives considered here with the same value of Q because R.D.X. has the highest rate of burning. However, we must remember that R.D.X/B.W.X. is at least a two phase system. When R.D.X. crystals are covered with Beeswax the cavities may be between these coated crystals. The sensitiveness would be much lower because beeswax does not burn (in the absence of air). Such a system should, therefore, be less sensitive than expected from the heat of explosion. It is possible that initiation occurs inside the crystals (c.f. pressed T.N.T. made with grains from cast T.N.T. of large and of small crystals) rather than in the wax between the coated crystals.

6.9 R.D.X. and P.E.T.N.

The quoted rate of burning of R.D.X. is definitely greater than that of P.E.T.N. (Table III) and these values agree approximately with the rates of burning of other nitramines and organic nitrates (ref 7). However, Bowden's work on cavity initiation of P.E.T.N. and R.D.X. (21) suggests that P.E.T.N. burns faster under his conditions than R.D.X. Nevertheless P.E.T.N. is, from all experience, (cavity initiation, impact sensitiveness and gap sensitiveness) more sensitive than R.D.X. R.D.X. crystals are harder than those of P.E.T.N. and, therefore, we cannot associate the difference with hot spots produced by intercrystalline friction although it is well-known that grit will sensitize R.D.X. and P.E.T.N. in impact tests. If R.D.X. does burn faster than P.E.T.N., then we must assume that some important factor has been omitted from our model.

7. DISCUSSION.

7.1 The results of our analysis can be summarized as follows:-

(a) the shock sensitiveness of liquids is determined by the value of the products $h \times C$ and $\rho_o Q$, the second factor becoming increasingly important as the confinement is reduced. This behaviour suggests that growth rather than initiation is the controlling factor in sensitiveness,

(b) the rate of burning is a major factor in the sensitiveness of all explosives,

(c) the sensitiveness of pressed T.N.T. charges can be reasonably explained by a combination of cavity initiation and growth,

Confidential.

Confidential.

(d) liquid T.N.T. apparently fits in with other liquid explosives but the value of the rate of burning is in doubt. The fact that liquid and cast T.N.T. have the same sensitiveness is probably a coincidence,

(e) the difference in sensitiveness between R.D.X. and P.E.T.N. may originate in physical, not chemical factors.

(f) in binary systems, the physical state of the binary system may be of major importance, e.g. RDX/BHX,

(g) in rifle bullet tests there is a correlation with gap sensitiveness in the case of liquid explosives. If there is a correlation in the case of solid explosives, it is a different one from that valid for liquid explosives.

7.2 The Gap Test.

We have obtained some knowledge of the shock pressures transmitted to the explosive in the E.R.D.E. gap tests. It has also been shown (Fig. 3) that a series of shocks is transmitted to the explosive so that the explosive charge is subjected to an "effective" pressure for a time, τ, which depends on the gap thickness. The consequence of this are analysed in Section 6.4. We can write $\tau = f(P)$, where P is the "effective" pressure. Clearly $f(P)$ will depend on the type of gap test, i.e. on the material of the gap and on the size of the donor charge.

For the purposes of analysis we have distinguished between initiation, by which we mean the starting of a combustion reaction at some point or points in the explosive, and growth at these points, i.e. a positive value of dP/dt at these points. Initiation may be by adiabatic compression of gas-filled holes in the explosive, i.e. cavities, but it is probable that this is not the mechanism in liquid explosives (see Section 7.4). If the charge is encased in metal, the shock from the gap will be transmitted to the containers as well as to the explosive. The particle velocities in the container and explosive will, in general, be different and viscous heating of the explosive at the boundaries may be the cause of initiation. It has been shown that confinement is an important factor in the growth process. It can be seen, therefore, that the type of container used for the explosive charge may be important.

The two preceding paragraphs can be summed by the statement that the sensitiveness measured by a gap test depends on the experimental technique as well as on the explosive. To illustrate these points we quote the following results:-

(a) We have that cast (normal brown) T.N.T. and liquid T.N.T. at 90°C have about the same sensitivity on Scales II and

Confidential.

       III. American workers (23) using a different experimental arrangements, found liquid T.N.T. to be appreciably less sensitive than cast T.N.T.,

(b) Dithekite D 13 is less sensitive than ethyl nitrate on Scale III but more sensitive on Scale I,

(c) J. Savitt (24) mentions that the relative sensitiveness of R.D.X. and Tetryl and of Composition A and T.N.T. is reversed when the container material is changed from brass to aluminium.

Originally this work on the gap test was started at E.R.D.E. on the assumption that the test was physically a simple one, i.e. the propagation of a single shock wave into the explosive. This is not true but the efforts made to obtain a better picture of the events in the gap test have helped to obtain a better understanding of the mechanism of sensitiveness. Thus points (a) and (b) above may be explicable in terms of the confinement factor. Point (c), if confirmed, probably cannot be explained in this way because a x Q and ΔQ for R.D.X. are larger than for tetryl and, therefore, under certain conditions there may be some mechanism of initiation other than cavity initiation, e.g. viscous heating, in which case the low temperature rate of decomposition of the explosive becomes an important factor.

7.3 Relation of gap test sensitiveness to results by other methods.

We shall restrict our discussion to impact sensitiveness. Measurements of impact sensitiveness are normally carried out with powdered explosives which have been lightly tamped. In such measurements the particles of the explosive can move relative to each other, i.e. frictional heating is possible, air pockets are enclosed in the explosive, i.e. cavity initiation is possible, and with certain types of striker plastic deformation of the striker can occur and thus a hot spot can be formed on the striker. With P.E.T.N., in the absence of grit the initiation appears to be cavity initiation (21), whereas, with some of the primary explosives, hot spots are formed by frictional heating or localised plastic flow in the crystals (21). According to Eyster et alia (23) the addition of grit to an explosive does not alter its gap test sensitiveness (called "booster" sensitiveness in the U.S.). For assessment of handling hazards, impact tests are more significant than gap tests, despite the fact that the results are generally qualitative.

Another important aspect of an assessment test is the criterion for a "positive" effect in a test. In gap tests we have used either the fragmentation of the container or the amount of damage to a thin metal cover plate. In impact tests, the volume of gas evolved by the explosive (Rotter Impact Machine) or the sound from an explosion is used as a criterion. Now the impact and gap pressures

required to produce these results may be different. With two explosives A and B, we may have the following state of affairs:-

$$R_b (A) < R_b (B) \text{ when } P < P_c$$
$$R_b (A) > R_b (B) \text{ when } P > P_c$$

i.e. A will appear less sensitive than B under one set of conditions and more sensitive under another set. Thus, at $P = 1000$ p.s.i., R_b (TNT) ~ 1.0 cm/sec (extrapolated from Table III) but may will be lower (see Section 6.4) and R_b (NH_4ClO_4) = 0.8 cm/sec but the rate of burning of T.N.T. appears to increase linearly with the pressure whereas that of NH_4ClO_4 increases as P^2 (unpublished data of Mr. G.K.Adams, E.R.D.E.). At low initiating pressures, i.e. loose powders in impact test, NH_4ClO_4 may be as sensitive or even more sensitive than T.N.T. but at initiating high pressures, i.e. compressed powders in gap test, should be less sensitive. Another case in point is cordite. Impact tests on cordites are always carried out with the finely divided material and under such conditions the cordites are quite sensitive. Gap tests measurements on cordite charges show that they are very insensitive. A good cordite charge has no pockets of gas and, therefore, cavity initiation is impossible. In manufacture, cordite is prepared either by a solventless or solvent process, i.e. the cordite is never in the form of a fine powder. Under manufacturing conditions the impact sensitiveness of finely divided cordite is irrelevant. If, however, it is necessary to machine or saw the cordite charges, the high impact sensitiveness of the finely divided powder is significant.

Nevertheless, there is a broad correlation between the gap and impact sensitivenesses of any explosives and we must ascribe this to the important role played by the rate of burning. Since, from the point of view of handling, explosive burning is a serious hazard, the low pressure rate of burning, which determines the sensitiveness of loose powders of solid explosives or a liquid explosive containing air bubbles, is probably a more important sensitiveness parameter than the high pressure rate of burning.

The case of composite explosives is considered in Section 7.5.

7.4 Liquid Explosives.

In the gap test measurement of the sensitiveness of liquid explosives we have shown that the results can be correlated the assumption that the growth of the explosion centre, and not initiation, is the controlling process. We do not yet know what the mechanism of initiation is but two possibilities must be considered:-

(a) very small air-bubbles in the liquid, and,

(b) local fluctuations in density in the liquid.

We can obtain an estimate of the minimum size of air bubble

Confidential.

From equation 2 of Appendix VI (the exact equation would give a higher value of the size). With $P_1 = 1$ atm. we have,

$$\tau_c = \frac{2qR}{\dot{m}c} \cdot T \cdot P^{(1-3\gamma)/3\gamma} = \frac{2}{\dot{m}} \cdot Q \cdot \lambda \cdot \frac{R}{c} \cdot \frac{1}{\dot{m}c} \cdot P^{(1-3\gamma)/3\gamma}$$

The uncertainties in the values of λ, c and γ are not important. If the gas in the bubble is air, we assume $\gamma = 1.4$, i.e. $(1-3\gamma)/3\gamma = -0.75$, $\lambda \sim 10^{-3}$ g/cm.sec. and $Ro \sim 10$ cal/mole. $\bar{\rho}$ is the density in the pre-combustion zone. The temperature in the cavity after adiabatic compression is high (about $3000°K$) and a value of $\bar{\rho} = 0.0001 P$ g/cm³ should not be in error by more than a factor of two even with $P = 10^4$ atms. For many liquid explosives $\dot{m} = \dot{m}_0 \times P$. With these values the equation above becomes:-

$$\tau_c \sim (2.5 \times 10^{-4} \times Q)/(\dot{m}_0 \times P^{0.75})$$

Some estimates of r_0 from this equation are given in Table XI.

TABLE XI.

MINIMUM BUBBLE SIZE FOR
CAVITY INITIATION IN GAP TEST.

EXPLOSIVE.	$\dot{m}_0$ g/cm² sec	Q cal/ gm	P atms $\times 10^{-3}$ pressure in gap test.	r_0 cm.
Ethyl Nitrate.	.008	754	4.7 (Scale III)	4×10^{-4}
Nitromethane.	.0023	969	14.3 (Scale III)	9×10^{-4}
Propyl Nitrate.	.0028	294	22.2 (Scale III)	1×10^{-4}
D.E.G.N.	.017	989	5.25 (Scale I)	2×10^{-4}

Since this is the minimum of gas bubble for initiation under the pressure conditions in the gap test which give a positive effect, and since we have shown that the results can be correlated with $\dot{m} \times Q$ (growth) and not with $\dot{m}/Q$ (cavity initiation), any bubbles really responsible for initiation must be larger than this, i.e. at least 10^{-3} cm. It is difficult to believe that degassed liquid explosives do contain bubbles of this size, except an occasional one.

It has been shown that addition of single bubbles (diameter 0.1 cm) to D.E.G.N. increases the sensitiveness very slightly (17). This must facilitate initiation but, since we have found growth to be the controlling mechanism, it would not be expected to have much effect on the gap sensitiveness.

It is known that there are density fluctuations in a liquid. When a liquid is compressed there must be local increases of temperature at the microscopic regions where the density, before compression, was below the mean density. For simplicity in calculation we shall assume that the liquid contains "holes". These "holes" will be distributed at random in the liquid but at any moment there is a finite possibility that any microscopic region contains more than the average number of holes. Such regions will be ones of low density.

We can estimate the minimum size of the regions in the following way. It was shown in ref 2 that the minimum size, r, of cavity in which combustion could be propagated was

$$\tau_c = \frac{\bar{a}\,\lambda}{\nu h\,c} = \frac{\bar{a}\,\lambda}{c\,P}\cdot\frac{1}{\nu_o}$$

With the values in Table XI we find that $r_o \sim 5 \times 10^{-5}$ cm. The energy necessary to start the combustion reaction is (2)

$$4\pi\tau_c^2 \varphi = \frac{4}{3}\pi\tau_c^3 \cdot \frac{P}{\varLambda}\,Q\cdot\frac{\lambda}{c}$$

which for ethyl nitrate is about 3×10^{-9} cals (values for the other explosives in Table XI range between 10^{-8} and 10^{-7} cals). This energy however, will not all be produced by adiabatic compression if the local rise in temperature is sufficient to decompose most of the explosive molecules in a time of the order of a few microseconds.

The number of calories released in a domain of radius r_o (initially) assuming that complete decomposition takes place, is

$$W_1 \times \frac{4\pi r_o^3}{3} \times \frac{P}{\varLambda} \times \frac{Q}{M} = 4 \times 10^{-10}\ \text{cal}$$

which is smaller than the required energy by a factor of 10 (allowance should be made for the fact that the reaction is a constant volume rather than a constant pressure reaction and the adiabatic heat of compression should be added but these corrections will not materially affect the result). This indicates that the complete decomposition of all the ethyl nitrate in such a cavity would not be sufficient to start the combustion reaction, i.e. the minimum cavity size would be about 10 times larger.

If the compression raises the temperature in the small domain from $T_o = 300^{\circ}K$ to $T^{\circ}K$, a thermal explosion will be produced in a time τ. Treating this thermal explosion as an adiabatic first-order process (which gives a minimum value of τ), it can be shown that

$$\tau \simeq \frac{\exp(E/RT)}{B}\cdot\frac{c\,RT^2}{QE}$$

For ethyl nitrate, $E = 39.9$ k.cals/mole, $Q \sim 70$ k.cals/mole, $\log B = 15.8$ and c (for ethyl nitrate vapour) ~ 30 cals/mole. With these values $\tau = 5 \times 10^{-4}$ secs, $T = 600^{\circ}K$; $\tau = 5 \times 10^{-6}$ secs, $T = 700^{\circ}K$; $\tau = 2 \times 10^{-7}$ secs, $T = 800^{\circ}K$. The delay before ignition on cavity initiation (2) is $\sim r_c/v$ which for ethyl nitrate ($P = 10^4$ atms, $v = 3$ cm/sec) is $\sim 10^{-4}$ sec. Experimentally the delay for D.E.G.N. containing a bubble when initiated by the gap test, Scale I, is about 40 micro sec. (17). Assuming that the hot spot must be formed in a time

Confidential.

certainly not greater than 100 μsec, T must lie between 600 and 700°K.

The bulk rise in temperature when water is adiabatically compressed to 10^4 atms. is about 35°C. We shall assume that this rise in temperature is bought about when some of the "holes" in the liquid are filled by compression, i.e. forcing molecules into them. If explosive liquids behave similarly (rough calculations on methyl nitrate (18) give a smaller rise in temperature) 10 times more moles are needed than exist on the average per unit volume of liquid in the domain of radius $10 r_0 = 5 \times 10^{-4}$ cm. in order to get a rise in temperature of 300 to 400°C. Since liquids at the melting point are 3% to 5% less dense than solids at the same temperature, we can say crudely that a liquid contains 3% to 5% "holes", i.e. places where molecules were in the solid state. This means that the liquid would have to have regions (with dimensions of 10^{-4} cm) of less than half the mean density. This is most unlikely.

The two possibilities discussed above are not mechanisms, therefore, for the initiation of liquid explosives in the gap test. Other possible mechanisms are viscous heating between the container and the explosive and concentration of shock waves by reflection from the container walls. Without further experimental data it is futile to speculate. However, even if the mechanism of initiation in the gap test is found, it may still give no explanation of how low velocity detonations propagate in nitroglycerine, methyl nitrate and diethylene-glycol dinitrate where the velocities of propagation are ~ 2000 m/s and the shock pressures are $\sim 10^4$ atms.

7.5 Solid Explosives.

On the model discussed in this report, we have shown that the sensitiveness of pressed charges of solid explosive can increase or decrease with density depending on whether the controlling factor is growth or initiation. Similar results have been found by American workers (20, 23). At densities near the absolute density initiation may be by another mechanism, i.e. by the temperature rise produced by compression of the bulk explosive. Our model thus accounts for the phenomenon of "dead pressing".

When we consider composite explosives, the picture becomes much more complicated. Compositions consisting of an explosive plus an inert component. e.g. RDX/BWX are considered in the first place. If the inert component completely covers each crystal of the explosive component, and if the crystals contain no gas-filled cavities, the composition should behave as inert material to pressures less than required for the initiation of "dead pressed" material. We can make an estimate of the thickness of inert layers in the following way, using RDX/Wax as our model. Let us consider crystals of diameter d cm, and cavities of diameter 2d (inspection of equation 4 of Appendix VI shows that this corresponds to a bulk density of about 1/9th of the absolute density). The thermal energy released in the cavity by adiabatic compression from a pressure of 1 atm. to

Confidential.

one of P atms is easily shown to be (assuming air in the cavity with
a molecular weight $\overline{M}$)

$$\frac{\pi}{6} \cdot (2d)^3 \cdot \frac{\overline{M} \times 1}{\overline{K}T_0} \cdot c \frac{(T-T_0)}{M}$$

where $P = (T/T_0)^{M \rho_1}$, $\gamma = 1.4$ and c = specific heat per mole. If P
is 1×10^4 atms, $T \sim 3000^\circ K$ and we can therefore neglect T_0 and obtain

$$\frac{M}{\gamma} \cdot d^3 \cdot \frac{cT}{\overline{K}T_0}$$

This heat is to be absorbed by the fusion of the inert material. If
the thickness of the inert material is t cm., its effective latent
heat of fusion, i.e. the energy required to raise the inert material
from T_0 to its melting point and to fuse it, L, and its density ρ_1,
then

$$\rho_1 \pi (2d)^2 \cdot t \cdot L = \frac{M}{6} \cdot d^3 \cdot \frac{cT}{\overline{K}T_0} \qquad \text{or} \qquad \frac{t}{d} = cT /(3\overline{K}T_0 \rho_1 L)$$

Assuming $T = 3000^\circ K$, $c = 10$ cal/mole, $T_0 = 300$, $\rho_1 = 0.8$ g/cm^3, $L = 50$ cal/g, $t/d \sim 10^{-2}$. If ρ_3 is the density of the explosive, the
percentage of inert material is $600 \cdot t/d \cdot \rho_1/\rho_e$. For RDX, $\rho_e = 1.8$ g/cm^3 and, for a wax, $\rho_1 = 0.8$ g/cm^3, hence about 3% of wax should
be sufficient to desensitise R.D.X. Usually about 10% is used but
Pennie and Sterling (25) report that 5% Beeswax or Aerawax is suffic-
ient to desensitise fine R.D.X. It should be noted that the density
of the wax does not enter into this calculation. The requirements
of the wax are that it should have a large heat of fusion, L, be
easy to spread over the explosive and adhere strongly to the surface
of the explosive so that it is not removed during handling. Since
for most purposes, a pourable explosive is required it follows from
this discussion that the minimum amount of wax is determined by
pourability rather than sensitiveness. A high density wax is clearly
undesirable if a pourable composition is required.

The T.N.T. in RDX/TNT compositions can be regarded as the
desensitiser and this is supported by the fact that these compositions
approximate to T.N.T., rather than R.D.X., in their sensitiveness
behaviour.

Composite explosives, such as NH_4ClO_4/TNT/Al, present a much more
difficult case for analysis. Such compositions, based on NH_4ClO_4/Al,
are sensitive to impact tests but relatively much less sensitive on
gap tests. In impact tests, there is plenty of air in the lightly
tamped composition so that oxidation of the aluminium may provide
the necessary hot spots, and friction and plastic deformation may
play a significant role. In pressed charges of this material there
is much less air and, therefore, the necessary oxygen to burn the Al
must be obtained from the NH_4ClO_4 which is thermally a very stable
material. It is not at all clear what the rate of burning of the
composite charge is relevant in this case. It has been shown that
pressed charges of NH_4ClO_4/TNT/Al are more sensitive, at the same
density, than cast charges of the same composition (26). We suggest
that, in the cast charges, the T.N.T. covers the aluminium so that

Confidential.

oxidation of the aluminium by the decomposition products of the NH_4ClO_4 is prevented. On this basis we can understand qualitatively why loose powders of the three components are as sensitive as R.D.X. on impact tests but relatively much less sensitive in gap tests and even more insensitive as cast compositions.

It was also found (26) that the gap sensitiveness decreased with decreasing density. As the density decreases the mean distance between fuel and oxidant components must increase. In order to get an exothermic reaction between the Al and the NH_4ClO_4, a diffusion flame must be set up between them and this will be more difficult the greater the separation.

Sufficient has been said to indicate the complications in interpreting the behaviour of composite systems. It is proposed to investigate the sensitiveness of binary mixtures of NH_4ClO_4 and certain fuels as E.R.D.E. has a wealth of combustion data on this type of system.

7.6 Rifle Bullet Sensitiveness.

It has been shown that there is a reasonable correlation between the sensitiveness of liquid explosives on the gap test and to rifle bullets. Since the gap test measurements can be correlated by the assumption that growth, and not initiation of explosion centres is the controlling mechanism, it is logical to apply the same conclusion to positive effects produced by rifle bullets. We say "positive effects" because the results produced by rifle bullets vary from mild explosions to complete detonations. Further, plastic propellants give a high percentage of explosions although their gap sensitiveness is low. As a possible explanation we have suggested that the "positive effect" in the rifle bullet test starts as a low pressure, i.e. $\sim 10^2$ atm, combustion process. Whether the rifle bullet causes this as a result of frictional heating of the explosive during its passage through the explosive, by forming a hot spot at the back or front of the container from the work done in piercing the container or by the production of shock waves is not known. Whatever the mechanism, however, we cannot expect the correlation between rifle bullet and gap test to be necessarily the same for liquids as that for solids because the initiation process in the gap test is different for the two classes of materials and we suggest that the initial pressure conditions in the two types of test are also different.

Two types of research will be necessary to clarify this crude picture. Firstly a detailed study of the time between impact and a positive effect with different masses and energies of fragment (bullet) under different confinement conditions. Secondly, a comparison of the rifle bullet sensitiveness and gap test sensitiveness of systems for which the R_b/P curves cross at some pressure. The following systems are quoted as examples:-

(a) ethyl nitrate and 2:3 butane diol dinitrate. It is known

that ethyl nitrate has the higher rate of burning at P ~ 100 atms. whereas it is less sensitive on the gap test Scale III.

(b) a plastic propellant with and without a combustion catalyst for which the catalysed composition will have the higher rate of burning at low pressure,

(c) T.N.T. and NH_4ClO_4 since R_b (TNT) increases linearly with pressure whereas that for NH_4ClO_4 increases as P^2, and,

(d) ethyl nitrate alone and catalysed with an amine (5).

8. CONCLUSIONS.

Our thesis is that the mass rate of burning combined with the heat of explosion, is a good criterion of the sensitiveness of a compound. In gap test measurements the high pressure (above 1000 atms) rate of burning appears to be relevant whereas in impact, and possibly in rifle bullet tests, the rate of burning at lower pressures appears to be important. However, with a given composition, the sensitiveness can be varied over a certain range by alterations in the density, grain size and crystal size or form (α and β H.M.X.). Completely satisfactory desensitisation implies that the energy per unit mass and the density of the explosive is not reduced. The method of application of the explosive also adds additional restrictions. Thus, if a pourable composition is required, e.g. RDX/TNT, RDX/PMX, the minimum amount of liquid phase required is probably above the minimum amount necessary for satisfactory desensitisation.

Desensitisation can be achieved basically in two ways. The first requires that the rate of burning should be reduced, with as little reduction in the energy as possible. Reduction in the rate of burning, without reduction in energy, has not been achieved except by mixing systems such as ethyl nitrate with nitromethane (Table I). The second way is to prevent mechanical action from producing hot spots in the explosive. For liquids, this means avoiding the presence of all gas bubbles in the liquid which is difficult. There is some indication, however, from Bowden's work (15) that, in impact tests, the viscosity may be of some importance. In the case of solids, we must reduce frictional heating, localised plastic deformation in the crystals and cavity initiation. In theory it is possible that some control of the first two factors can be achieved by modifications to the crystal form. All three factors can be controlled to some extent, by coating the high energy components with soft materials such as waxes. We have suggested that ~ 3% wax should be sufficient to desensitise a compound such as R.D.X., against cavity initiation but we do not know whether such small quantities would be effective in impact tests with grit present. We can see that, with such small quantities of desensitiser, the physical properties of the desensitiser, apart from the relevant thermal ones and the ability to adhere strongly to the explosive, are of minor importance. The

Confidential.

greater the quantity of desensitiser, the more important become properties such as density and energy content. Of these, the density is probably most important since detonation pressure is approximately proportional to the energy per unit mass, but to the second power of the density. A high density desensitiser increases the difficulty of application because its volume is smaller.

It is shown in ref 7 that the rate of burning at pressures of 30 atms. is a monotonic function of Q but that explosives can be divided into three broad classes: nitramines, nitroxy compounds and nitro-compounds, the rate of burning at a given Q decreasing in this order. American workers have realised that the aliphatic nitrocompounds offer a fruitful field of research and have specifically looked for a substitute for T.N.T. in this field. R.D.X. and H.M.X. are good explosives because of their stability, fairly high energy content and high density. The efficient utilisation of these explosives requires either,

(a) desensitisation with small quantities of high density desensitisers, or,

(b) combination with an aliphatic nitrocompound with the minimum reduction in energy and density.

Class (a) will give compositions which cannot be poured, but must be press-filled. Class (b) can give pourable compositions. The application of these ideas to explosive systems will be discussed in another report at a later date.

REFERENCES

1. E. K. Rideal and A.J.B.Robertson.   Proc. Roy. Soc. 1949 A 195, 135

2. G.K.Adams & L.A.Wiseman.   E.R.D.E. Tech. Memo. No. 2/M/52.

3. R.Pape & E.G.Whitbread.   E.R.D.E. Tech. Memo. No. 21/M/52.

4. L.A.Wiseman.   E.R.D.E. Report No. 42/R/51.

5. G.K.Adams & G.W.Stocks.   E.R.D.E. Report No. 1/R/51.

6. G.W.Stocks.   E.R.D.E. Report No. 10/R/50.

7. G.K.Adams & L.J.Drummond.   E.R.D.E. Report No. 4/R/53.

8. G.K.Adams & G.O.Lloyd.   E.R.D.E. Report No. 10/R/53.

9. A.F.Belayev & A.E.Belayeva.   Comptes Rendus (Doklady) 1946, 52, 805.

Confidential

10.	S.J.Jacobs & W.B.Buck.	O.S.R.D. Report No. 6329.
11.	R. Page.	E.R.D.E. Tech. Memo. 8/M/54.
12.	A.F.Belajov & A.E.Belajeva.	Comptes Rendus (Doklady) 1947, 56, 491.
13.	K.K.Andreev.	Comptes Rendus (Doklady) 1946, 54, 39.
14.	L.P.Jones.	E.R.D.E. Report No. 29/R/51.
15.	F.P.Bowden & A.D.Yoffe.	The Initiation & Growth of Explosion in Liquids and Solids. Cambridge University Press 1952.
16.		A.R.E. Memo. No. 1/51.
17.	R.Page & R.G.Whitbread.	E.R.D.E. Report No. 17/R/52.
18.	O. Ratner.	Acta Physiochimica URSS 1947, 22, 357.
19.	O.K.Hartman.	N.O.L. Memo. 10,768.
20.	R.H.Stresau & L.E.Starr.	N.O.L. Memo. 10,577.
21.	F.P.Bowden & O.A.Gurton.	Proc. Roy. Soc. 198A (1949) p.350.
22.	K.A.Cooper, E.Speller & E.G.Whitbread.	E.R.D.E. Tech. Memo. No. 11/M/51.
23.	E.H.Eyster, L.C.Smith & S.R.Walton.	N.O.L. Memo. 10,336.
24.	J.Savitt.	Navord Report 2997.
25.	A.M.Pennie & T.S.Sterling.	C.A.R.D.E. Tech. Memo. 77/52.
26.	C.C.Lovenberg.	Navord Report 2589.

APPENDIX I.

HEATS OF FORMATION.

COMPOUND.	HEAT OF FORMATION ($-\Delta E_f$).
Ethyl Nitrate.	42.0
Propyl Nitrate.	48.0
Nitromethane.	25.1
2 - Nitropropane.	38.9
2:3 Butane diol dinitrate.	72.9
Diethylene Glycol Dinitrate.	107.0
Nitroglycerine.	85.4

Confidential

HEATS OF FORMATION - (CONTINUED).

COMPOUND.	HEAT OF FORMATION ($-\Delta H_f$).
Nitric Acid.	41.4
Nitrobenzene.	- 3.5
Ethyl Alcohol.	66.1
Methyl Nitrate.	35.4
Ethylene Glycol Dinitrate.	61.0
Triacetin.	306.0
CO_2.	94.05
CO.	26.41
H_2O (gas).	57.80
H_2O (liquid).	68.30
Hydrazine (liquid).	- 12.05
Hydrazine Nitrate.	60
Mercury Fulminate.	65.4
Trinitrotriazidobenzene.	2/?
Potassium Picrate.	110.1
Lead Styphnate.	107
R.D.X.	- 14.4
P.E.T.N.	126.7
Tetryl.	- 6.0
T.N.T.	10.2

These values are not, in all cases, the best ones. Thus, Gray
& Smith (J.C.S. 1954, 769) quote a value of ΔH_f = -45.8 k.cals/mol for
Ethyl Nitrate and a recent redetermination of ΔH_f (CH_3NO_2) has brought
it back to the old value of -27 k.cals/mole. The main sources used
were:-

(a) Springall and Roberts.   A.R.D. Report No. 614/44.
(b) H.M.M.Pike.   A.R.E. Report No. 25/49.
(c) Robinson.   Thermodynamics of Firearms. Hill
                                                              1943.

APPENDIX II.

MAXIMUM RATE OF BURNING.

All explosives can burn to detonation. The mechanism, in most
cases, is that the combustion gases penetrate into the mass of the
explosive. This leads to a mass rate of burning per unit area which
is much greater than the true mass rate of burning. Under such con-
ditions pressure gradients will be formed and eventually shock waves.
Since the gas flow into a shock front is always supersonic, the shock
wave will move into the explosive and detonation may result because
rates of burning normally increase with pressure. There is another
possibility, however, if the true mass rate of burning is high
enough a shock wave will be formed as soon as combustion commences.

Confidential.

i.e. true combustion is not possible since detonation intervenes.

Since the gas flow into a shock front must be supersonic intuitively one feels that an approximately necessary condition for this type of phenomenon is that the gas flow from the burning surface should be sonic. The sonic velocity, a, is defined by $a^2 = \gamma RT/M$ where:- γ = specific heat ratio., T = temperature of combustion gases, and M = molecular weight of combustion gases. The gas flow velocity from a burning surface is $v = \dot{m}/\rho = \dot{m} RT/PM$, where ρ = density of combustion gases, and P = pressure of combustion gases, i.e. initially of surrounding atmosphere. On our argument detonation and not combustion will occur if $v > a$. We can then determine a critical value of $\dot{m}$, $\dot{m}_o$, defined by

$$\dot{m}_o = P\left[\frac{\gamma M}{RT}\right]^{1/2}$$

Since T here Q = heat of explosion and c = specific heat per unit mass, we   write

$$\dot{m}_o \simeq P\left[\frac{\gamma M c}{RQ}\right]^{1/2}$$

With Q = 500 cal/gm,   bout 30, γ = 1.2 and c = 0.4 cal/gm. deg. C, the value of $\dot{m}_o$ at P = 1 atm., is about 20 gm/cm^{2}sec.

A more rigorous analysis (Navord Report 90 - 46) leads to the expression.

$$\dot{m}_o = \gamma P\big/\left[2c(\gamma^2-1)\right]^{1/2}$$

If c is a specific heat at constant volume, the exact expression is smaller than the "intuitive expression" by a factor, $(2(\gamma + 1)/\gamma)^{1/2} \simeq 2$ If c is a specific heat at constant pressure, the factor is $(2(\gamma + 1))^{1/2} \simeq 2$. Thus, the maximum rate of combustion, when gases do not penetrate into the explosive is, at P = 1 atm., about 10 g/cm^2 sec., which is far greater than the rate of combustion of any materials outside the initiator class (see Table III of text). It is possible that in the azides, particularly lead, thallous and silver azides, the true rate of burning is greater than $\dot{m}_o$ and therefore a hot spot goes over to detonation without an intermediate combustion regime. Bowden and Williams (Proc. Roy. Soc. 1951, 208A, 176) have shown that, with thin films (about 0.1 mm. thick) of the azides mentioned above, there is no build up to detonation but detonation occurs immediately on initiation.

APPENDIX III.

COMPOSITION OF PLASTIC PROPELLANTS IN TABLE IV.

Code No. of Composition	NH₄ ClO₄	Ammonium Picrate.	Polyiso- butylene.	Poly- styrene. Parts by weight.	NaNO₃	Lecithin
E 202.	86.5	-	12.5	-	-	1
E 260.	76.5	10	12.5	-	-	1
E 261.	66.5	20	12.5	-	-	1
RD 2200.	89	-	-	10	-	1
RD 2043.	-	55	-	10	34	1
RD 2331.	36.5	50	12.5	-	-	1
RD 2332.	26.5	60	12.5	-	-	1

-- -- -- -- -- --

APPENDIX IV.

PROPAGATION TEST.

Most tests of "detonability" are, in reality, tests of propaga-
tion. In the usual form of this test the material to be examined is
filled into a number of charge cases of about equal lengths but
different diameters, and attempts are made to initiate these charges
with primers, the size of which increases with charge diameter. In
general the ability to support a detonation wave is greater at the
larger diameters and with the more massive confining tubes. Tube
strength is of secondary importance since the pressures involved in
a detonation (about 10^5 atms.) are greater than the yield point of
any material.

In practice a standard set of charge cases is used, each case
with its own size of primer, and the result is quoted as the smallest
size of tubing in which the material will propagate detonation. Such
a set of tubes is given below.

Inside Diameter.	Wall Thickness.	Primer.
2"	8 gauge.	60 grams Tetryl.
1½"	8 gauge.	40 grams Tetryl.
1"	16 gauge.	20 grams Tetryl.
½"	16 gauge.	10 grams Tetryl.
½"	16 gauge.	5 grams Tetryl.
¼"	15 gauge.	Detonator only.

Diameters greater than 2 inches are seldom used because of the quantity of explosive involved. With diameters smaller than $\frac{1}{4}"$, the charge case is joined on to a section of larger diameter to accommodate the detonator.

APPENDIX V.

COMBUSTION IN A CAVITY.

1. **Basic Equation.**

Let V be the volume of the cavity in an explosive in which combustion is occurring. The mass, $m(t)$ of gas (combustion products) in the cavity at time t is:- $m(t) = V(t). \rho_g(t)$.   1.

where $\rho_g(t) =$ density of gases in cavity. If we assume that the gases behave as ideal gases (consideration of imperfect gases is given later), $\rho_g = P\Sigma/RT$, whence:-

$$\delta_{\rho_g} = \frac{\Sigma}{R}\left[\frac{1}{T}\delta P - \frac{P}{T^2}\delta T\right]$$
     2.

where $P =$ pressure, $T =$ temperature, $\Sigma =$ mean molecular weight of gases (assumed independent of P and T), $R =$ gas constant.

At time $t + \delta t$, $m(t + \delta t) = m(t) + 4\pi r^2 R_b \rho_o \delta t$, where $r =$ radius of cavity, $R_b =$ linear rate of burning of explosive (cms/sec), $\rho_o =$ density of explosive (the compressibility of the explosive is neglected).

$$\rho_g(t+\delta t) = \rho_g(t) + \frac{\partial \rho}{\partial t}\delta t = \frac{m(t+\delta t)}{V(t+\delta t)} = \frac{V(t)\rho_g(t)+4\pi r^2 R_b \rho_o \delta t}{V(t) + 4\pi r^2 \delta r}$$
     3.

where $\delta r =$ increase in radius in time δt.

Substituting equation 2 in equation 3 and noting that $V(t) = (4/3). r^3$ we obtain

$$\rho_g(t) + \frac{\Sigma}{R}\left[\frac{1}{T}\frac{dP}{dt} - \frac{P}{T^2}\frac{dT}{dt}\right]\delta t = \frac{\rho_g(t) + \frac{3}{r}.R_b\rho_o\delta t}{1 + \frac{3}{r}.\frac{dr}{dt}.\delta t}$$
     4.

which neglecting terms in $(\delta t)^2$, leads to

$$\frac{1}{T}\frac{dP}{dt} - \frac{P}{T^2}.\frac{dT}{dt} = \frac{3}{r}\left[R_b\rho_o\frac{R}{P\Sigma} - \frac{P}{T}\frac{dr}{dt}\right]$$
     5.

2. **Value of dT/dt.**

In time δt, the radius of the cavity increases by δr and the mass in the cavity by $4\pi r^2 R_b \rho_o \delta t = m$. We shall now divide this process into two stages:-

    (a) addition of hot gases of mass, δm, the radius changing from r to $r + R_b\delta t$, no work is done at this stage,

    (b) expansion of cavity from $r + R_b\delta t$ to $r + \delta r$ without addition

Confidential.

of hot gases.

(a) If T_0 is the initial temperature of the explosive then $m(t).c.$
$(T' - T_0) + Q.4\pi r^2 R_0 \rho_0 \delta t = (m(t) + 4\pi r^2 R_b \rho_c \delta t).c.(T' - T_0)$, where
T' = temperature after addition of mass m of hot gases, Q =
heat of explosion at constant volume at T_0, c = mean specific
heat at constant volume (T-to T).

By rearranging the above equation we obtain:-

$$T - T_c = \frac{3}{r} \cdot \frac{R}{M} \cdot \frac{R_b \rho_c T (Q' - cT') \delta t}{c^2 P} \qquad 6.$$

(b) For adiabatic expansion - $P = \text{const.} \, r^{-\gamma}$ (where γ is different
from the low temperature, low pressure value). Whence $dP/P =$
$-\gamma dV/V = -3\gamma \, dr/r$

Further $P = \text{const.} \, T^{\gamma/(\gamma-1)}$ whence $dP/P = \frac{\gamma}{\gamma-1} \cdot \frac{dT}{T}$ Therefore $dT/T =$
$-3(\gamma-1)\frac{dr}{r}$ or $\frac{-T'-T'}{T'} = -3(\gamma-1)\frac{\delta r}{r} \qquad 7.$

where T'' = temperature after expansion of cavity from $r + R_b(t)$
to $r + \delta r$. The value of δr is $(R_b + A)\delta t$, where A is the linear
rate of expansion under the hydrodynamic forces, i.e. δr in
equation 7 is $A\delta t$.

From equations 6 and 7

$$T'' - T = \frac{3}{r} \cdot \frac{R}{M} \cdot \frac{R_b \rho_c T (Q' - cT') \delta t}{c^2 P} - 3(\gamma-1)\frac{R_b \delta t T'}{r}$$

which can be written

$$\frac{1}{T} \cdot \frac{dT}{dt} \simeq \frac{3}{r}\left[\frac{R}{M} \cdot \frac{R_b \rho_c (Q' - cT)}{cP} - (\gamma-1)A\right] \qquad 8.$$

since $T' \simeq T$.

3. Rate of Increase of Pressure in Cavity.

Equation 8 can be substituted into equation 5 to give

$$\frac{1}{P} \cdot \frac{dP}{dt} \simeq \frac{3}{r}\left[\frac{R_b \rho_c T}{M} \cdot \frac{R}{M} + \frac{R_b \rho_c (Q' - cT)}{cP} \cdot \frac{R}{M} - \frac{dr}{dt} - (\gamma-1)A\right]_9.$$

Now $dr/dt = R_b + A$, where A, a complex function of P and the conditions
of confinement, is the rate of growth of the cavity under the pressure
in the cavity. Equation 9 can, therefore, be written

$$\frac{1}{P} \cdot \frac{dP}{dt} = \frac{3}{r}\left[\frac{R}{M} \cdot \frac{R_b \rho_c Q'}{cP} - \gamma\left[\frac{R_b}{\gamma} + A\right]\right] \qquad 10.$$

4. Imperfect Gases.

Instead of assuming that $PV = nRT$, we can take the next approx-
imation or $P(V - nb) = nRT$, where b = a constant, n = the number of
moles of gas in volume V. It follows from this that $\rho_g = PM/(RT+bP)$
If the above analysis is repeated with this value for ρ_g, we obtain:-

$$\frac{1}{P} \cdot \frac{dP}{dt} = \frac{3}{r}\left[\frac{R}{M} \cdot \frac{1+\alpha}{cP} \cdot R_b \rho_c (Q' + \alpha cT) - \gamma\left(\frac{R_b}{\gamma} + A\right) - \alpha(R_b + A)\right]$$

Confidential.

where $\alpha = bP/RT$, which is similar to equation 9.

5. Effect of Number and Size of Cavities on Confinement Factor A in Equation 10.

Let us imagine that the charge, during the build-up process, is expanding at a rate of E (cm^3/sec) per unit volume of explosive and that the increase in volume is obtained entirely by expansion of the cavities under the hydrodynamic forces, i.e. the compressibility of the condensed phase is neglected. Let there be n cavities, which have a radius r at pressure P, per unit volume of explosive. We then have:-

$$n \cdot 4\pi r^2 \cdot dr_c/dt = E$$

or

$$\frac{dr_c}{dt} = A = \frac{E}{4\pi} \cdot \frac{1}{n r^2}$$

12.

where dr_c/dt is defined by $dr/dt = R_b + dr_c/dt = R_b + A$ as in Section 3 of this appendix.

- - - - - - - - - - - -

APPENDIX VI.

INITIATION IN A CONDENSED PHASE CONTAINING CAVITIES.

1. It was shown in ref 2 that the pressure required to produce initiation by the adiabatic compression of gas in a cavity of initial radius r_c was given by the equation

$$r_c = \frac{3\kappa R (P_i/P_o)^{2/3\gamma}}{\dot{m} c P_i \left[\left(\frac{P_i}{P_o}\right)^{\gamma-1/\gamma} + \frac{p}{P_i} \cdot \frac{M'}{M} \cdot \frac{q}{c} \cdot \frac{T'}{T_o} \right]}$$

where:-
$q = 3^2 \cdot Q \cdot b/a$,
$\bar{\rho}$ = mean gas density at moment of initiation,
Q = heat of explosion,
κ = thermal diffusivity of gas,
$\dot{m}$ = mass rate of burning at pressure P,
P_i = initial pressure,
P_o = initiating pressure,
R = gas constant,
M = mean molecular weight of gases in cavity,
M' = molecular weight of explosive vapour,
c = specific heat,
p = vapour pressure of explosive in cavity,
γ = specific heat ratio,
T' = mean temperature in cavity at moment of initiation, and,
T_o = initial temperature.

Now if $\dot{m}$ is a linear function of pressure, q is approximately independent of pressure since $k\bar{\rho} = \lambda/c$ is also approximately independent of pressure. For most explosives p is very small and the term containing

Confidential.

this can be neglected. In ref 2, it was estimated that T'/T_0 was about 3 and therefore if $P_0 \sim 10^3$ atms. we can also neglect this term. Equation 1 can therefore be written

$$\tau_c = \left[\frac{3 q_v R}{M_c} \cdot P_i^{-1/3\gamma} \right] \cdot \left[P_0^{(1-2\gamma)/3\gamma} \right] \qquad 2.$$

whence $\log r_0 = \log D' - B \log P_0$. Where $D' = (3q_v/M_c) P_i^{-1/3\gamma}$ and $B = (2\gamma-1)/3\gamma$

2. Equation 2 will now be applied to a pressed charge. Let the charge be made up of particles of explosive of grain size d. If the density of the explosive is d_0 and that of the pressed charge is δ. the number of explosive particles per unit volume of pressed charge is
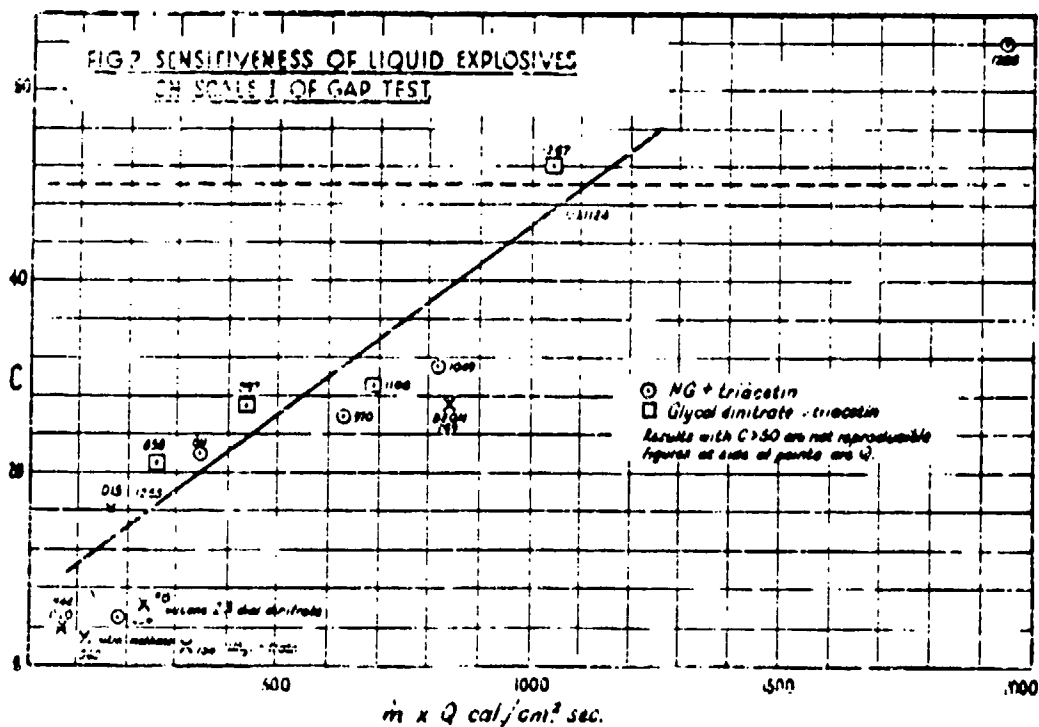
$$n \cdot \frac{\pi}{6} \cdot d^3 \cdot \delta_0 = \delta \qquad \text{or} \qquad n = \frac{6}{\pi} \cdot \frac{1}{d^3} \cdot \frac{\delta}{\delta_0} \qquad 3.$$

The fraction of free space is $(\delta_0 - \delta)/\delta_0$ and if we regard this as distributed over n cavities per unit volume of diameter d_0, we obtain $n \cdot \frac{\pi}{6} \cdot d_0^3 = (\delta_0 - \delta)/\delta_0$ which, on substituting the value of n from equation 3, leads to $d_0 = d \sqrt[3]{(\delta_0 - \delta)/\delta}$

d_0 of equation 4 is equal to $2r_0$. The pressure required to initiate a pressed charge by a cavity initiation is thus given by

$$\log d + \frac{1}{3} \log \left[\frac{\delta_0 - \delta}{\delta} \right] = \log D - B \log P \qquad 5.$$

where $D = 2D'$.

FIG 1. SENSITIVENESS OF LIQUID EXPLOSIVES ON SCALE III OF GAP TEST.

$\dot{m} \times Q$ cal./cm² sec.

FIG 2. SENSITIVENESS OF LIQUID EXPLOSIVES ON SCALE I OF GAP TEST

$\dot{m} \times Q$ cal./cm² sec.

FIG. 3

→ TIME |_20µ sec._|
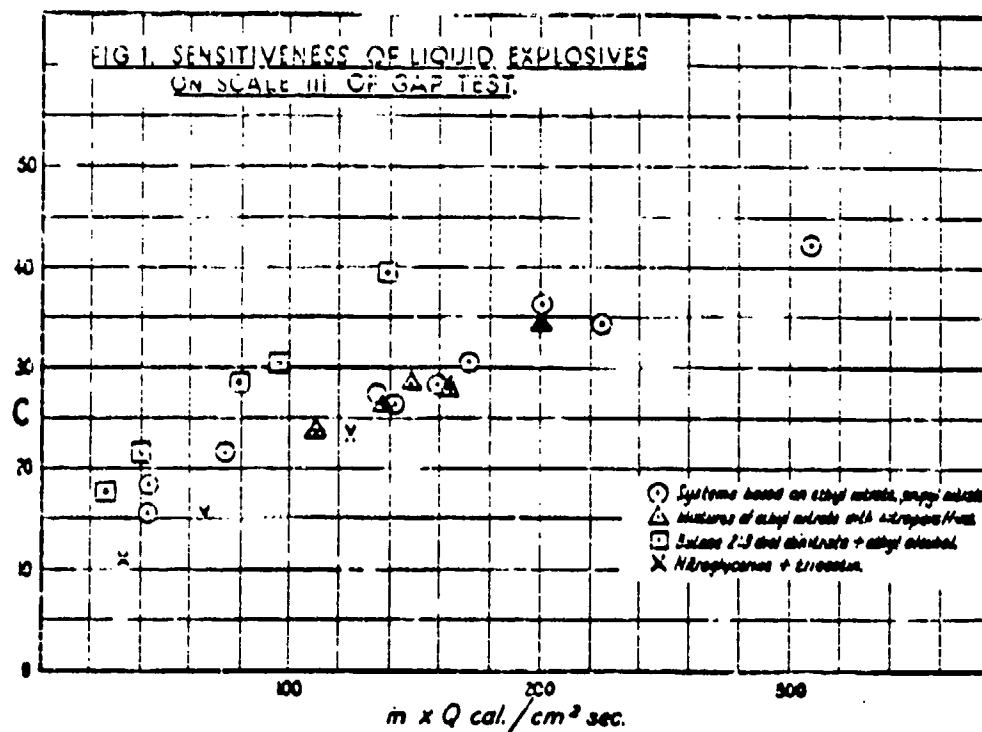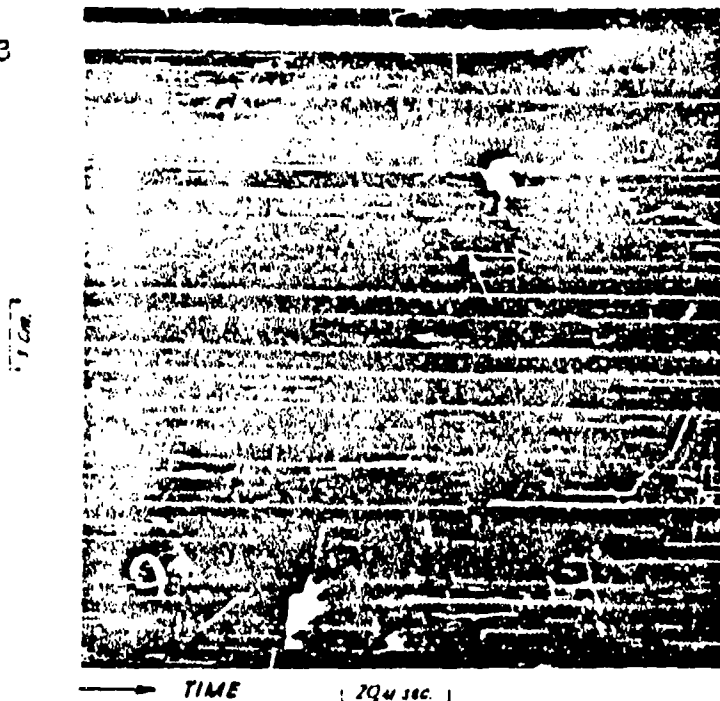
Mirror Camera photograph showing multiple shocks and reflections in Scale II type test (Water in perspex tube)

FIG 4. SENSITIVENESS ON SCALE I
m x Q AS FUNCTION OF ρc Q

figures beside point are C values (Scale I)

$\dot{m} \times Q$ cal/cm² sec.

ρc Q cal/cm²

73

FIG 5 PRESSURE vs CARD VALUE

P(atms)

- pressure by optical measurement.
— pressure by pressure bar.

C (card value)

FIG 6a SENSITIVENESS OF T.N.T. (Small Crystals)

B.S. Sieve Ranges
0 10 to 25
1 25 to 52
2 52 to 72
3 72 to 100
4 100 to 150
5 150 to 200

C

Scale 2.

Liquid TNT at 90°C

Cast TNT

Density g/cm³

FIG 6b SENSITIVENESS OF TNT (large crystal)

Density g/cm³

FIG 7 SENSITIVENESS OF PICRIC ACID

Density g/cm³

PROBLEMS OF INITIATION IN TESTS OF SENSITIVENESS   3

E.G. Whitbread
E.R.D.E., Ministry of Supply
Great Britain

SUMMARY

The prime purpose of tests of sensitiveness is to assess the probability of accidental explosion occurring in explosive charges of practical size.   Information is accumulating at E.R.D.E. that in the case of some tests of sensitiveness it is the chance of growth, not of initiation, that is assessed.   In this category are the 'Gap' test and tests of sensitiveness to attack by small arms ammunition and by high-velocity fragments, possibly excepting when they are applied to materials of a high order of sensitiveness such as R.D.X.

Perhaps the most important part of this information is the proved correlation between sensitiveness and an arbitrarily defined 'rate of energy release' deduced from combustion data.   The correlation, however, tends to break down for materials of high sensitiveness, and also fails for plastic propellants and colloidal propellants (cordits).

Recent work at E.R.D.E. on the mechanism of tests by projectile attack has revealed induction periods of up to 500 microseconds between impact and explosion, thus confirming the importance of the growth phase.   There is evidence of two mechanisms operating in the explosion process though it is probable that their overall pattern is the same, the features contributing to the pattern varying in degree. The particular mode prevailing is a function of the level of sensitiveness of the explosive tested, and this may result in tests of the 'Gap' type being much less reliable criteria for very sensitive explosives than for, say, liquid monopropellants.

If, with a particular explosive, it is clear which of the three phases of the explosive reaction is the most significant, initiation, growth or propagation, and if this is also the controlling phase under the conditions prevailing in the 'Gap' test, then the results

will be of value even if relating to a different parameter and showing wider scatter than with the liquid propellants.

INTRODUCTION

Sensitiveness tests are usually performed in order that the chance of an explosion in a charge of practical size may be estimated. In such a practical charge initiation is usually important only when accompanied by the subsequent growth of the explosion process.

There is a growing body of information at E.R.D.E. that in a number of tests of sensitiveness the mechanism of the test is related to combustion processes, and that what is being measured is not the probability of initiation but the rate of growth of the process once initiated. If this is so, then the properties measured by these tests will not be the same as those measured by other tests which do, in fact, measure initiation (e.g., some impact machines). If the data are to be intelligently used it will be necessary to decide both what is required and what is provided by the tests used.

TYPES OF TEST CONSIDERED

1. Gap Test.

It has been observed by several authors - notably Eyring (1) - that some tests, particularly those using a high-intensity shock to initiate the explosive, give results which are very reproducible. In order to put sensitiveness studies on a quantitative basis it was therefore decided at E.R.D.E. some years ago to use the 'gap' test. The precise forms used at Waltham Abbey have been described elsewhere (2) and it is sufficient for the purposes of this paper to state that there are two patterns of immediate interest, described as Scales I and III, the major differences being (a) that in Scale I the case used to contain the charge under test is lighter than that used in Scale III, and (b) that whereas in Scale I the criterion of a 'fire' is the fragmentation of the charge case, in Scale III it is the rupture of the test plate placed on the top of the charge under test. In both cases the result obtained is a number, known as the 'card value', which increases with increasing sensitiveness.

2. Projectile Tests

Since in the past it has been believed to be of 'practical'(as opposed to 'academic') importance, and because the results have some significance in relation to the 'gap' test, a considerable volume of work has been done on the 'rifle bullet attack' test and on the 'high-velocity fragment attack' test. In these tests the explosive is subjected to projectile attack while confined in a container, the subsequent condition of which, in conjunction with blast effects, is used to determine whether or not a charge has exploded.

EVIDENCE AVAILABLE

In an analysis of the results obtained by the foregoing tests (3)
it was shown:-

(a) That sensitiveness, as measured
by Scale III (which deals with less
sensitive explosives than does
Scale I), correlates linearly with
the product $\dot{m}Q$, where $\dot{m}$ is a mass
rate of burning under monopropellant
conditions at an arbitrary pressure,
50 atmospheres, (the units of $\dot{m}$ are
$ML^{-2}T^{-1}$) and Q is the heat of
explosion (water gaseous) at
constant pressure. The data are
summarised in Table 1 and graphically
represented in Fig. 1.
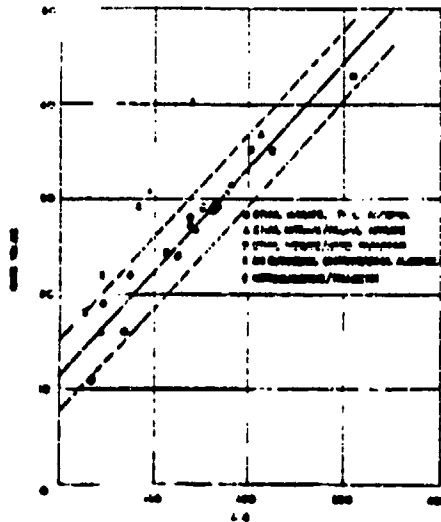
For any two-component system
(e.g., ethyl nitrate/ethyl alcohol)
the correlation between sensitive-
ness and the combustion data is
excellent, deviations from the
linear relation amounting usually
to one unit (card) of sensitiveness.
As can be seen from Figure 1, the overall correlation is very good;
if the case of 2:3 butanediol dinitrate is excepted the regression
coefficient is 0.95, which is significant at the 0.001 level for the
number of materials tested. It is of interest that even the 2:3-
butanediol dinitrate system shows the correlation between sensitive-
ness and $\dot{m}Q$ when considered by itself.

(b) That a linear relation exists
between the percentage explosions
obtained in the 'rifle bullet'
test and the sensitiveness as
measured by the 'gap' test,
Scale III (and therefore, the
'rifle bullet' results correlate
with $\dot{m}Q$) (Fig. 2.).
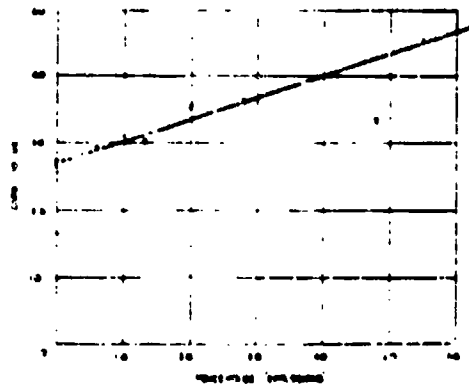
Percentage explosions in the Rifle bullet
Test Vs. Card Value (Cap Test Scale III).
Fig. 2.

Confidential

Table ___

Sensitiveness of liquid explosives in Scale III.

No	Explosive		C		q	z			C #
	Component I, %	Component, %	g/cm³	mm/sec	cal/g	g/cm²/ mm	cal/cm²/ mm	cal/cm³	
	Propyl Nitrate	**Ethyl Alcohol**							
1	100	0	1.11	0.37	754	0.41	309	937	43
2	96	4	1.09	0.31	662	0.308	224	728	35
3	92.1	7.9	1.08	0.26	572	0.281	161	618	29
4	90.4	9.6	1.07	0.24	533	0.257	137	570	28
5	84.1	15.9	1.05	0.18	388	0.189	73	457	22
6	80.1	19.9	1.03	0.14	287	0.144	48	306	19
	Ethyl Nitrate	**Propyl Nitrate**							
7	80	20	1.10	0.29	648	0.319	211	728	37
8	70	30	1.10	0.26	616	0.286	176	673	31
9	60	40	1.09	0.23	570	0.251	143	631	27
10	0	100	1.05	0.14	294	0.147	43	309	16
	Ethyl Nitrate	**Nitromethane**							
11	60	40	1.12	0.19	839	0.213	179	940	31
12	40	60	1.13	0.15	883	0.170	150	998	29
13	0	100	1.14	0.10	969	0.114	110	1105	24
	Ethyl Nitrate	**Nitro mixtures**							
14	80	20	1.11	0.24	757	0.266	201	840	35
15	70	30	1.12	0.19	759	0.213	168	890	30
16	60	40	1.12	0.16	761	0.179	136	852	27
	2,3 B.D.D.N.	**Ethyl Alcohol**							
17	96	4	1.27	0.15	738	0.191	129	936	40
18	92.1	7.9	1.24	0.121	637	0.150	95	790	31
19	90.4	9.6	1.23	0.108	605	0.134	81	744	29
20	84.1	15.9	1.19	0.070	400	0.074	42	531	22
21	80.1	19.9	1.16	0.063	353	0.073	25	409	18
	Nitroglycerin	**Triacetin**							
22	57.5	32.5	1.41	0.172	686	0.247	169	779	14
23	65	35	1.42	0.150	592	0.240	124	889	14
24	60	40	1.39	0.104	464	0.162	66	636	13
25	55	45	1.36	0.074	336	0.101	33	457	11
26	0.15 #		1.37		1265				24
27	0.20 §		1.36		1146				19

* C is a measure of the thickness of the gap. The gap consists of cards and C is the number of cards in the critical size of gap.

Nitromixtures = 63% Nitromethane + 17% 2-Nitropropane

^ 0.15 = 34.4% Nitrobenzene : 62.4% Nitric Acid : 3% Water

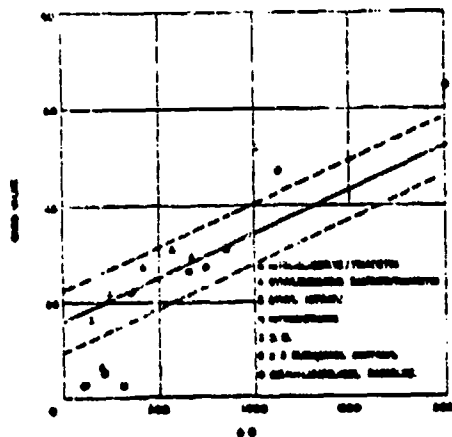§ 0.20 = 22.6% Nitrobenzene : 57.4% Nitric Acid : 20.0% Water

c 2,3-Butane diol Dinitrate

Confidential

(c) That no simple correlation could
be found between ΔQ and the card
value for the materials tested on
Scale I (i.e., for the more sensitive
class of materials) (Table 2) Fig.3.)

While the bulk of the work
described deals with liquids, ex-
tension to solids is under way.
The most outstanding result so far
is that the plastic propellants and
cordites, when fired in the form of
a single card, are very insensitive,
as judged on the basis of the ΔQ
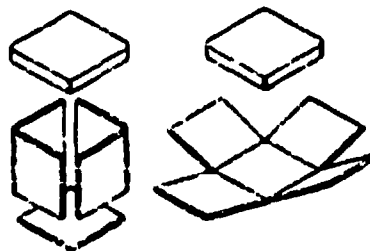relation. (Table 3).

While it is important that,
eventually, the mechanisms for all
tests of sensitiveness are under-
stood, work directly aimed at the
evaluation of mechanism has, at
E.R.D.E., been restricted to the
'fragment' and 'rifle bullet' tests.
In view of the links both have with
ΔQ, it is probable that similar
mechanisms will be found for both
the projectile and the Scale III
'gap' test. The details of the
results of this investigation are
as follows (4):-

(a) The tests are very sensitive
to the construction of the
container, for example, a change
in the proportion of welded to
folded edges has been found to
have a marked influence on the results. Ethyl nitrate, fired in a
box constructed as shown in Figure 4(a), gave 60% of explosions, but
if the box was made as in Fig. (b) the percentage of explosions fell
to 40, a significant decrease in the 50-shot samples used.

(b) The tests are relatively insensitive to the energy of the
projectile, provided that this exceeds some minimum value. Thus if
in a steel box of uniform thickness a 'window' of varying thickness
is fitted at the point of entry of the bullet, the results shown in
Table 4 are obtained. The slight increase in lethality with thick-
ness of entry windows from 1/16 to ¼ inch is not statistically
significant in the sample size (50 shots) used. The sharp decrease
at 5/16 inch is significant and would seem to indicate that the
projectile must have a certain minimum energy for initiation; but if
it has this minimum energy, the probability of explosion is determined
mainly by the explosive container. If the thickness of the whole

CORRELATION BETWEEN SENSITIVENESS (CARD VALUE
SCALE I) AND RATE OF ENERGY RELEASE FIG.3

FIG.4a   FIG.4b

TABLE 2.

Sensitiveness of liquid explosives in Scale I

No.	Explosive Component 1	Component 2	ρ g/cm³	λb cm/sec	q cal/g	$\dot{q}$ g/cm²/sec.	$\dot{q}\rho$ cal/cm² sec.	ρq cal/ cm³	C *	Group
1	Nitroglycerin	Triacetin	1.54	0.52	1330	1.51	2208	2048	46	C
2	90	12	1.50	0.44	1170	0.96	1123	1755	47	C
3	85	15	1.48	0.52	1050	0.78	850	1644	31	B
4	82.5	17.5	1.47	0.44	1000	0.65	685	1483	26	B
5	80	20	1.45	0.29	840	0.42	327	1231	22	B
6	75	25	1.42	0.20	720	0.285	205	1022	5	A
	70	30								
	Ethyleneglycol dinitrate	Triacetin								
7	89	11	1.45	0.559	1240	0.81	1012	1811	52	C
8	84	16	1.43	0.427	1091	0.61	646	1560	29	B
9	82.5	17.5	1.42	0.378	1044	0.54	544	1482	31	B
10	80	20	1.41	0.304	966	0.43	415	1354	27	B
11	75	25	1.39	0.214	823	0.30	247	1144	21	B
12	Ethyl nitrate		1.11	0.37	754	0.41	308	837	2	A
13	Nitromethane		1.14	0.10	949	0.114	110	1105	3	A
14	D.13.		1.37		1265	0.177	1486	1733	16	B
15	D.20.		1.36		1146			1238	4	A
16	Butane 2:3 diol dinitrate		1.30b	0.19	824	0.235	194	1074	6	A
17	Diethyleneglycol dinitrate		1.37	0.61	877	0.848	744	1219	27	B

* C is a measure of the thickness of the gap.   The gap consists of
cards and C is the number of cards in the critical size of gap.

† †q (and hence †) obtained from Figure 1.

Confidential.

Table II

Low Gas Scale III Sensitiveness of Plastic Propellants

Code Number of Composition	Density gm/ml.	Rate of Burning at 1000 p.s.i.		q cal/gm	$\rho z q$ cal/cm^2/sec	(% free from air)	C containing air)
		cm/sec	gm/cm^2/sec				
E242	1.70	1.99	3.06	948	2931	16	
E250	1.69	1.91	2.508	646	2167	15	
E261	1.48	1.12	1.646	775	1391	10	
E911 (E248 + 3% Cr$_2$O$_3$)	1.73	2.23	3.893	931	3024	15	22
E912 (E250 + 3% Cr$_2$O$_3$)	1.71	2.70	3.620	640	2673	12	20
E913 (E261 + 3% Cr$_2$O$_3$)	1.69	1.70	2.873	751	2198	10	16
E937 (E242 + 3% K$_2$Cr$_2$O$_7$)	1.71	1.45	2.480	950	2356	12	
E938 (E250 + 3% K$_2$Cr$_2$O$_7$)	1.68	1.19	1.999	360	1719	10	
E939 (E261 + 3% K$_2$Cr$_2$O$_7$)	1.66	0.94	1.560	770	1202	10	
RD.2200	1.78	1.88	3.346	1140	3815	30	
RD.2203	1.73	0.73	1.134	453	541	10	
RD.2231	1.60	0.30	0.488	409	240	10	
RD.2332	1.58	0.25	0.375	404	160	10	10

Notes:- (1) These propellants are putty-like materials made by coating a salt oxidant with a high polymer binder.

(2) The air content of the 'Free from air' material is about 1%.

(3) The rates of burning are for 1000 p.s.i., data in other tables in this report are for 50 atm. The correction factor, which is not known exactly, should not be less than 0.75.

Confidential

Table B

Compositions of Plastic Propellants

Composition	Parts by Weight					
	Ammonium Perchlorate	Ammonium Picrate	Polyiso-butylene	Polystyrene binder	Sodium nitrate	Lecithin
X202	86.5	-	12.5	-	-	1
E250	76.5	10	12.5	-	-	1
E261	66.5	20	12.5	-	-	1
RD.2200	89	-	-	10	-	1
RD.2043	-	75	-	10	14	1
RD.2331	36.5	50	12.5	-	-	1
RD.2332	16.5	60	12.5	-	-	1

Table C

Gap Test Scale III Sensitiveness of Cordite

Cordite	Density gm/ml.	Rate of burning 30 Atm. gm/sec. mm/mm²/sec.		gals/gm.		Card Value
		N	A	a	A	c
SC	1.576	0.43	1.15	310	931	10
SC Chopped *	1.0					(a) 31
						(b) 34
LS	1.575	0.21	1.28	550	590	10
P.188/649	1.550	0.24	1.30	670	670	10

* 'SC chopped' consists of pressed charges, made from chopped SC
cord, (a) of diameter and length = 0.205 inch each, and
(b) of diameter and length = 0.048 inch each.

Table 4

Variation in Lethality with Thickness of Point of Entry

Rifle Bullet Attack – 3 inch Cubical steel boxes of
1/8-inch Wall thickness filled with Ethyl Nitrate

Thickness of 'Window' (inch)	Percentage Explosions	Total Number of Trials
1/16		50
1/8		50
3/16		50
1/4	30	50
5/16	0	6

Table 5

Variation in Lethality with Thickness of Wall

Rifle Bullet Attack – 3-inch cubical steel
boxes, filled with Ethyl Nitrate.

Thickness of Wall (inch)	Percentage Explosions	Total Number of Trials
1/16	0	20
1/8	60	25
3/16	40	20

box is varied, and not just the point of entry, then there is a profound effect on the lethality, as is shown in Table 5.

The way in which the energy of the projectile is made up (i.e., the relative importance of mass and velocity) has a considerable effect on the lethality. Boxes made by welding 1/16 inch sheet steel end plates to 3-inch long sections of $3\frac{1}{2}$ inches O.D. x 8 gauge pipe were attacked by high-velocity fragments and rifle bullets, the projectile passing axially through the box. The results with ethyl nitrate are given in Table 6, and it can be seen that, compared with the 1.7 gm. fragment, the 7.5 gm. fragment is not more lethal, in spite of its increased energy, and that the rifle bullet is (in this context) quite harmless!

When using boxes with perspex windows, high-speed photography of the entry cavities produced showed that, whereas the rifle bullet made a clean tunnel through the liquid, the bomb fragment made a large hemispherical cavity. It was thought that the blast pressure from the bomb used to drive the fragment was inflating the cavity through the entry hole, thus artificially increasing the surface and internal pressure, an effect absent in the case of the bullet. A number of shots were fired in which bombs without fragments were used to attack filled boxes with a previously made hole. In no case did initiation occur, nor was any cavity formed. It would seem, therefore, that the greater lethality of the smaller fragment, as compared with the bullet, is a real phenomenon and not produced by the experimental conditions.

(c) It is possible to observe a delay between the impact of the projectile and the explosion. Three methods have been used in this work:-

(i) varying the construction, and thereby the bursting time, of the box,

(ii) high speed cinematography, and

(iii) observation of the light evolved from the box, by means of a photomultiplier coupled to a cathode ray oscillograph.

The third method gives results more suited to exact analysis than the other two, and by the use of a number of mixtures of differing ΔQ the variation of the delay with this parameter has been observed.(Table 7 Fig.5), and the delay found to be
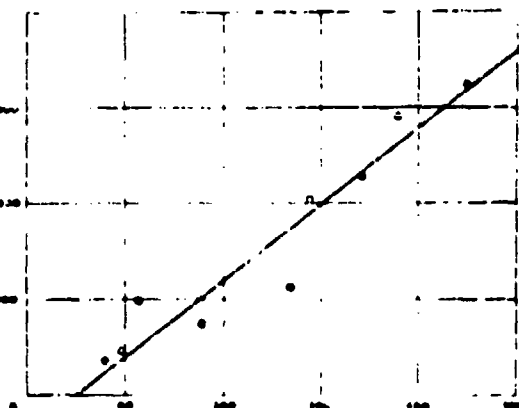
Confidential

Table 6

Variation in Lethality with Projectile.
'Pipe' - type bombs filled with Ethyl Nitrate.

Projectile and weight	Energy (Joules)	Percentage Explosions	Total Number of ...
Fragment 1 gm.	2.50×10^5	32	25
Fragment 1.7 gm.	7.54×10^5	24	50
Fragment 7.5 gm.	0.70×10^5	10	20
Bullet 11.5 gm.	3.18×10^5	0	20

Table 7

Delay in Occurrence of Flash in the
Rifle Bullet Test as a function of ΔQ

Explosive		ΔQ (cals/gm./cm³)	$\frac{1}{\Delta Q}$	Delay (microseconds)
Component A	Component B			
Ethyl Nitrate	Nitroglycerine			
100	0	300	0.00344	444
95	5	363	0.00281	377
85	15	457	0.00228	341
80	20	600	0.00204	283
48	52	1010	0.00199	119
23	77	2140	0.00247	97
0	100	2784	0.00236	91
Nitromethane	Nitroglycerine			
44	56	904	0.00111	270
34.5	65.5	1376	0.00073	178

Confidential

inversely proportional to $\dot{\Delta}Q$.

DISCUSSION

In view of the correlation with $\dot{\Delta}Q$ for both 'Cap' and Projectile tests, it would appear reasonable to suppose that we are dealing not with initiation itself but with the growth of the process subsequent to initiation, and that this process is similar to combustion.

Examining the relation between the delay and $\dot{\Delta}Q$ in the rifle bullet test shown in Table 7 (Fig. 5), it can be seen that it is of the form:-

$$D - A = \frac{k}{\dot{\Delta}Q}$$

where D = measured delay A and K are constants.

Since $\dot{\Delta}Q$ is a rate of energy release per unit area it follows that $k/\dot{\Delta}Q$ is the time for some given quantity of energy to be produced. It is not surprising, therefore, that this will correlate with the observed delay from impact to some defined phenomenon such as the appearance of light. What is surprising is the length of the delays (up to nearly 500 microseconds) which can only re-emphasise that the rate of energy production in the early stages must be low, as, by consequence, must be the pressure.

The actual observation in a series of rifle bullet tests is the probability of explosion, as determined by the proportion of boxes actually exploding under set conditions. Initiation by any one or more of what might be termed the primary processes (i.e., shock produced by impact, viscous heating of the liquid flowing round the projectile, heating by the projectile which has itself been heated by its passage through the front plate, and 'nipping' of the explosive between the projectile and the back plate) occurs in the first 120 - 150 microseconds, and where the delay is longer than this there is strong presumptive evidence that the chance of explosion is not the chance that one of these processes will occur, but is rather the probability that a subsequent process is allowed to continue without interruption. Such a conclusion is supported by the relative insensitivity of the tests to the energy of the projectile and by their sensitiveness to the nature of the construction of the box. The high lethality of a small fast fragment appears anomalous but is explained later.

The most likely sequence of events is that one, or more, of the 'primary' processes starts a combustion-like reaction which either builds up to an explosion or is stopped by the dispersal of the system, and it is the variations in the middle stage that produce the variation in the results when different explosives are tested.

The way in which the rifle bullet test depends for its

Confidential

discrimination on the differing rates
of energy release is now reasonably
obvious. Consider Figure 6 in which
energy release, E, is plotted against
time, T. A given energy release
history is plotted on this diagram
as a curve through the origin. Three
such curves corresponding to rates R_1
R_2 and R_3 are shown. (It is not
assumed that the shapes shown are
correct). In most forms of the test
(5) 'Partials' are recognised as well
as 'Detonations', (so called); these
correspond to levels of energy release
E_1 (Partial) and E_2 (Detonation).
If we take a box of definite design,
then the bursting time under the
conditions of the test will vary in
a statistical manner between limits
T_1 and T_2. Now, for an explosive
corresponding to R 100 per cent.

Fig. 6

of detonations will be observed since the R_1 energy release line
reaches E_2 before T_1; for R_2 there will be a statistical distribution
of 'Partials' and 'Detonations', and for R_3 the prior advent of time
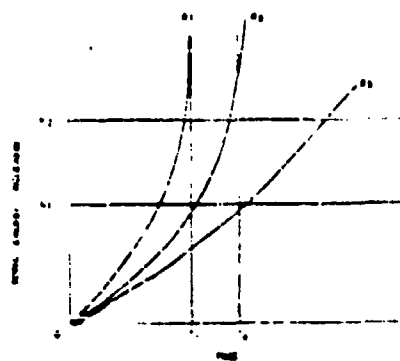T_2 will always ensure a failure.

The two constants in the expression $D - A = \dfrac{K}{\dot{E}Q}$ have a physical

meaning. If $\dot{E}Q$ is infinite, energy is released at an infinite rate
and the intrinsic delay must be zero. We are, however, considering
the delay from impact to the observation of light when using a steel
box; to be observed, the light must get out of the box, so that
either the projectile must go right in or, alternatively a split
must appear in the box itself. 'A' represents this delay and will
be roughly constant for all explosives. It was checked by the
substitution of an all-perspex box for the usual steel one, using a
filling of pure nitroglycerine; the observed delay was reduced, but
the dispersion of D about the regression line for delay on $1/\dot{E}Q$ is too
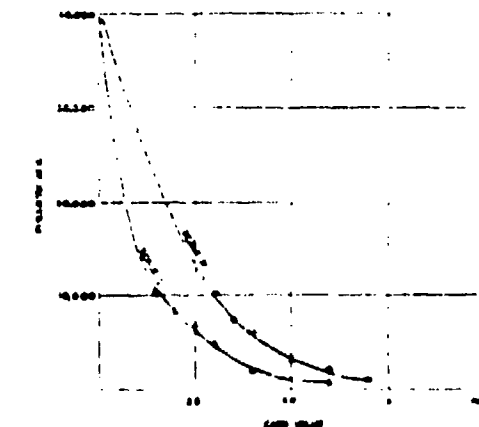great for A to be accurately measured by this experiment.

K is much more interesting than A. If $D - A$ is a time and $\dot{E}Q$ a
rate of energy release per unit area, K must have the dimensions of
energy per unit area and represent the ratio of the total energy
required to satisfy the criterion of a fire (in this case the light
flash) to the area of reacting surface available. Now the surface
available will be due largely to the material shattering under stress,
and this is a very complex phenomenon depending (in the case of a
liquid) on viscosity and tensile strength. It is interesting to
note that all the liquids used to compile Table 7 have similar
viscosities (their tensile strengths are unknown) and it is probable
that if a major change in viscosity had been made the correlation

Confidential

would break down. It is possible that the increased lethality and
the large cavity produced by the small fast fragment as opposed to
the bullet is due to the lack of aerodynamic form and to the tumbling
motion of the former, producing a larger zone of 'shattered' liquid.
An attempt was made to check this by using 'dum-dum' bullets (i.e.,
with the ogive truncated); the cavity was altered in shape and the
delay reduced, but not significantly so in a statistical sense.

In the case of the 'Gap'
Test, the most important
evidence for the existence
of a slow combustion stage
is the correlation between
the card values and com-
bustion data measured at
a pressure which is very
low (50 Atm.) compared with
the pressures measured by
the Hopkinson Pressure Bar
on the 'gap' surface. (6)
(Figure 7.) It is unlikely
that the pressure exponents
will be so consistent that
the relative rates of
burning for different
explosives will be the same
at the 10^3 to 10^4 atm.,

Hopkinson Pressure Bar Measurements
on Gap Test Card Stacks. (Fig. 7).

shown in Figure 7, as they are at 50 atm. The reaction will be
stopped in the gap test not so much by dispersal - as in the
projectile test - since the tube is often recovered, but by the onset
of rarefaction waves from the top of the tube, and, ultimately,
through the 'gap' itself. The time available for the induction
period probably increases with increasing 'gaps' (because the gap is
thicker the rarefactions take longer to enter the explosive), but
this is more than offset by the decreasing pressure behind the shock
front.

Solids may be divided into more or less porous solids and
homogeneous types such as cordite. In the former, the area of
reacting surface is largely determined by the internal structure
(i.e., by grist, crystal size, etc.); in the latter, we have materials
which may be considered as liquids of enormous viscosity and con-
siderable tensile strength. These will yield very small reacting
areas (i.e., high values of K) and their intrinsic delays will be
long, i.e., the probability of explosion is low.

There is no a priori reason why all 'gap' and 'projectile' tests
should not conform to this scheme, and some explanation is necessary
for the 'Scale I' results. If these data are examined (Table 2)
they will be seen to fall into three groups (marked A, B and C in
the table). Of these, group A correlates with ΔG in the same

Confidential

manner as to the materials tested by 'Scale III', i.e., there is a
relation of the form:

$$C = a + b \ (\triangle Q)$$

The values of the constants a and b are, however, different for the
two scales. It is thought that group A has failed to correlate
because it consists of materials which, in the size of tubing used
as a charge case, will fail to propagate a detonation. Since
criterion of a 'fire' is that the tube is shattered, the test is not
applicable to such materials which are certain to give anomalous
results. By reference to Table 2 it will be seen that they all have
relatively low values for ρQ, the energy density, and this indicates
lack of ability to propagate detonation, particularly in small
diameters where the energy losses due to the lateral expansion of
the confining tube in the region of the reaction zone are high. The
reason for the failure in the correlation in materials of high $\triangle Q$
(i.e., those in group C) is more subtle, and in some respects more
important. It is known that for 'gaps' in excess of 50 cards on
'Scale I' the pressure in the shock front is below 1000 atm. (6)
(Fig. 7), and that under these conditions the attenuation is no
longer exponential or reproducible (a peculiarity of the cardboard
system). This, however, is not the whole story since, if the
correlation has been obeyed, then with at least two of the materials
card values of less than 50 should have been obtained. A probable
reason for the failure is that for material of high $\triangle Q$ the build-up
of the reaction from initiation is so rapid that it is not possible
to extinguish it by mechanical dispersal. The limit for control
in this way, must vary with the system, and for 'Scale I' appears
to have been reached at $\triangle Q = 850$ cals./sec.cm^2.

CONCLUSIONS

It is concluded that there is a common mechanism for all
explosions in the tests described viz:- (i) initiation of a
combustion, (ii) increase in rate of burning and extent of combustion
surface, (iii) a change to detonation if the burning surface has a
velocity exceeding the local speed of sound, thus generating a
shock wave. It is with the probability of the third step, detonation,
or, if this does not occur, the virtual completion of the second by
the consumption of all the available material, that we are concerned
in sensitiveness testing.

Within this general pattern occur two modes of operation. If
the second stage is slow - because of a low rate of burning, low
energy or too little surface available for combustion - then it will
become important because, being slow, it will provide a delay in
which it is possible to "put out the fire." If, however, the
second step is fast then every initiation becomes a detonation and
we must measure the chance of initiation.

Confidential

It has been seen that our tests commonly measure the rate of growth, i.e., step (ii), but that in some cases (e.g., explosives of high mQ) they might measure chance of initiation because in the test the second step is fast. The question then arises: does the test provide the information required for all explosives for which mechanical considerations (such as the failure of large cardboard gaps) do not preclude its use? To answer this question, we must know the operating mechanism in the explosion of the practical charges which are our primary concern. The investigation of this while not more difficult, is much more expensive than the corresponding work with small charges, and may be prohibitively so. We have, however, some information: it is certain that if delays are not important in a small charge, they are even less so in a large one. No-one doubts that if nitroglycerine (an extreme case) is initiated there is no way of stopping it; the difficulty is that even with less sensitive explosives, if they are in the form of a large charge, every initiation may become a detonation simply because the transit time of the shock wave and the returning rarefaction is so great that, without the aid of confinement, there is ample time for the 'growth' stage.

We have little information to enable us to decide at what size a particular explosive will pass into this class, but if the importance of such tests as the 'gap' test is to be assessed it will have to be obtained.

BIBLIOGRAPHY

1. H. Eyring, Chem.Rev., 45 1 69-181, 1949.
2. R. Pape and E.G. Whitbread, E.R.D.E. Tech. Memo. 21/M/52.
3. L.A. Wiseman - E.R.D.E. Report 42/R/51.
4. P.C. Hobbins and E.G. Whitbread - E.R.D.E. Report in preparation.
5. L.F. Jones - E.R.D.E. Report 29/R/51.
6. R. Pape - E.R.D.E. Tech. Memo. 8/M/54.

LEAD AZIDE PRECIPITATED WITH POLYVINYL ALCOHOL   4

T. Gaynor Blake
Olin Mathieson Chemical Corporation
East Alton, Illinois

Donald E. Seeger
Picatinny Arsenal
Dover, New Jersey

Richard H. Stresau
Naval Ordnance Laboratory
White Oak, Maryland

Introduction

Although the virtues of lead azide as an initiating explosive have long been known, its use has been somewhat limited by the hazards involved in uncontrolled crystallization. Accidental explosions which occurred in early manufacture were variously explained in terms of large crystals, twin crystals and formation of the beta polymorph. Many materials have been used for the purpose of directing the formation of the stable alpha form during the precipitation. The best known cryst 1 controlling material, which is also the most used in the United States is dextrin (1). Typical dextrinated lead azide contains between 92 and 95% lead azide.

The British have used a material termed "Service" lead azide (2), characterized by a minimum lead azide content of approximately 97%. The crystal control of this material is achieved without the use of an organic protective colloid. Due to its higher purity, "Service" lead azide will usually out-perform dextrinated lead azide, but its handling and storage characteristics are less desirable.

During World War II, in the loading of detonators containing Service Lead Azide, some United States installations experienced prohibitively high rates of

Confidential

inadvertent explosions during the pressing operations. This led to attempts in the chemical laboratories to modify the lead azide in order to reduce the handling hazards, while maintaining the desirable characteristics of service Lead Azide.

One of the resulting lead azides which seemed to have improved sensitivity characteristics was a sample precipitated in the presence of polyvinyl alcohol (3), hereinafter referred to as PVA lead azide, and having a lead azide content somewhat reduced from that of Service Lead Azide. This material, however, was not approved for production prior to the end of World War II. In 1949, the Naval Ordnance Laboratory began an investigation of the properties of this lead azide, which led to the discovery of some interesting characteristics. These characteristics include low hygroscopicity, an ability to accelerate to maximum rate of detonation in a shorter period of time (and column height), and a slight increase in the terminal rate for the same loading pressures.

Dextrinated Lead Azide (75X)
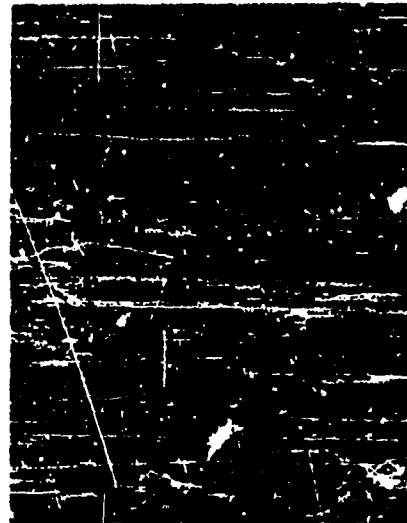
Polyvinyl Alcohol Lead Azide (75X)

FIGURE I

Experimental

During the development of the T196E4 (M505) Fuze for use in 20 mm. ammunition, it became evident that a detonator smaller than the standard M29 detonator (which was the smallest available at that time) would be needed in order that the safety requirements could be realized. The

space available for the detonator, later to be designated the T32, was approximately .145" in diameter and .290" long. It was required that this detonator be capable of initiating high order detonation in an RDX booster charge across a minimum air gap of .050".

At the outset of the development of the T32 detonator, the PA-100 and Standard Primer Mixtures, dextrinated lead azide, tetryl, PETN and RDX were the only explosives standard for use in detonators. It soon became evident that, using these materials, the optimum explosive train was one made up of PA-100 Primer Mixture, dextrinated lead azide and RDX. A shellac coated gilding metal cup, hand loaded with these explosives produced a detonator that met the requirements set forth and functioned satisfactorily in fuzes. However, since the critical weight tolerances required on the charges of explosive of this detonator could not be held in mass production, the detonator failed to satisfy the need. In order that such a small detonator could be mass produced, it was necessary to look for more efficient explosive materials.

Information on the availability of new explosives and explosive mixtures suggested two paths of solution to the problem. One involved the use of a more efficient primer mixture; the other the use of a more efficient lead azide. This problem was finally resolved after exhaustive investigation and subsequent adoption of the NOL No. 130 Primer Mixture. It was found that as little as 5 mg. of this primer (compared with 25 mg. of PA-100 Primer Mixture) is required to initiate dextrinated lead azide reliably. The quantity of primer mixture used in this detonator was therefore cut to approximately one-half the amount originally used. The space made available was used by increasing both the dextrinated lead azide charge and the RDX charge. This detonator, designated originally as the T32E1 Detonator and finally standardized as the M47 Detonator has been mass produced with little difficulty.

During the investigation of the second possible solution to this problem, several new types of lead azide were investigated. Among these was the Polyvinyl Alcohol (PVA) lead azide. Modified T32 Detonators loaded with this lead azide in place of the standard dextrinated lead azide proved to be far superior from a functioning point of view. Figures II, III and IV show results of T32 Detonator shellac coated gilding metal cups loaded with 30 mg. of PA-100 mixture and the intermediate and base charges as noted. Each charge was consolidated at 10,000 p.s.i. As noted, the space available from the decrease in the lead azide charge was filled with base charge.

Confidential

Quantity (mg.)   Hole Size (Inch)

PbN$_6$	RDX	PETN	#Tested	HO	LO	Ave.*	Max.	Min.*
100		30	50	50	0	.227	.248	.209
95		34	50	49	1	.223	.250	.164
90		38	50	37	13	.220	.237	.203
85		40	50	25	25	.223	.247	.207
80		42	50	33	17	.228	.250	.180
75		44	50	30	20	.230	.250	.204
70		46	50	33	17	.232	.261	.200
65		48	50	11	39	.227	.248	.200
60		51	50	0	50	-	-	-
55		54	50	0	50	-	-	..
100	28		50	50	0	.229	.248	.212
95	32		50	50	0	.233	.250	.214
90	36		50	50	0	.233	.251	.213
85	40		50	50	0	.227	.252	.187
80	44		50	24	23	.218	.242	.172
75	46		50	0	50	-	-	-
70	48		50	0	50	-	-	-
65	50		50	0	50	-	-	-
60	52		50	0	50	-	-	-
55	52		50	0	50	-	-	-

Figure II

PbN$_6$	RDX	#Tested	HO	LO	Ave.	Max.	Min.
80	45	50	50	0	.258	.289	.233
75	48	50	50	0	.258	.278	.231
70	51	50	50	0	.260	.281	.237
65	54	50	50	0	.263	.284	.237
60	57	50	50	0	.266	.294	.231
55	60	50	49	1	.267	.306	.205
50	61	50	49	1	.264	.293	.212
45	62	50	49	1	.266	.293	.170

Figure III

Similar tests were conducted in a modified T42E1
Detonator. In this case the shellac coated gilding metal
cups were loaded with 13 mg. of NOL No. 130 Primer Mixture,
lead azide and RDX as noted. Each charge was consolidated
at 15,000 p.s.i.

Confidential

Quantity Dex. PbN_6	RDX	#Tested	#HO	#LO**	Lead Disc Hole Size*		
					Ave.	Max.	Min.
110	36	45	45	0	.212	.232	.177
100	41	45	45	0	.218	.244	.170
90	45	45	45	0	.194	.229	.031
85	49	45	44	1	.219	.251	.159
80	52	45	28	17	.149	.214	.075
75	55	45	2	43	.163	.245	.081
70	56	45	0	45	-	-	-
65	58	45	0	45	-	-	-

PbN_6	RDX						
70	60	45	45	0	.260	.308	.230
60	62	45	45	0	.267	.291	.230
55	64	45	45	0	.254	.298	.206
50	67	45	45	0	.263	.303	.206
45	70	45	45	0	.252	.290	.192
40	72	45	45	0	.259	.302	.231
35	74	45	44	1	.224	.275	.186
30	76	45	45	0	.236	.276	.197

* Low order detonation not included in hole size.
**Low order - no hole in lead disc.

Figure IV

As can be seen from the data presented in Figures II, III and IV, PVA lead azide is twice as efficient as an intermediate charge for use in small detonators as the standard dextrinated lead azide.

Under Project "Jackstraw" one of the approaches to the problem called for the design of a very small stab type primer-detonator having great sensitivity. This detonator was to occupy a space having a diameter of .145" and an overall height of 1.40". Moreover, there was a section at the base of the cylinder which had a diameter necked in to .090". This detonator was required to initiate high order detonation of an RDX-Hystrene (98-2) lead across a .035" air gap. Because earlier fuze design work on this task had been carried out with the M26 primer which appeared to have almost the desired sensitivity, the first efforts were toward increasing the initiating ability of the M26. It was very quickly found that neither the sensitivity nor the required initiating ability could be achieved.

The successful approach was made as follows:
Using the cup described above and holding the initiator
constant at a value considered to be well above minimum,
the base charge was progressively reduced to determine the
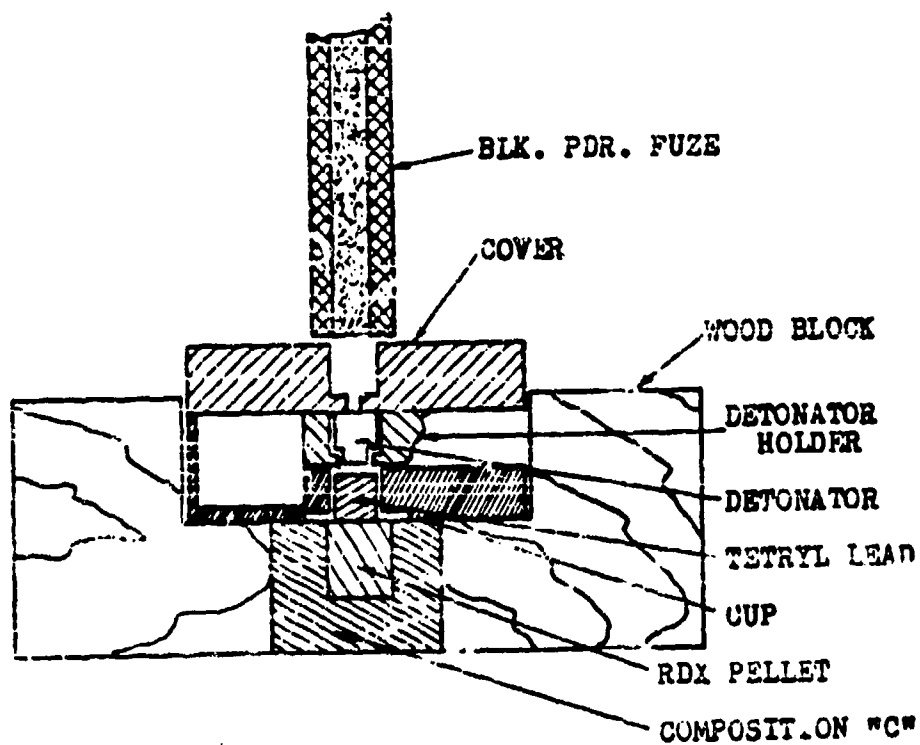minimum quantity which would give the initiating power re-
quired.

In order to eliminate the variables associated
with sensitivity and firing pin shape, the lead azide
charge was subjected to the spit of a section of safety
burning fuse. Because with the small quantities of explo-
sive the degree of confinement provided by the test fixture
was considered to be extremely critical, it was decided
that measurements such as plate indentation should be
avoided and the test shots would be in fuze rotors which
in turn would fire the normal lead and the ability of this
lead to propagate to a booster would be determined by hav-
ing the lead shoot a small sample of Composition-C con-
tained in a wood block. Figure V, Drawing A-2 shows this
test fixture. This proved to be a very noisy test and the
wood blocks were, of course, completely demolished when a
high order detonation was achieved. On the other hand, it
eliminated any possibility of misinterpretation of results
because the Composition-C, in those cases where the detona-
tor was sub-marginal was merely scattered around and the
wood block was not destroyed. At this time three base
charge materials were under consideration, tetryl, PETN and
RDX, in the belief that small differences in their sensi-
tivity to initiation and output might be significant in
achieving a workable system.

Having determined the minimum quantity of base
charge, this was held constant and the minimum initiating
charges, both of dextrinated and PVA lead azide were
determined. In this case it was found that less than 30 mg.
of PVA lead azide would initiate the base charge high order
whereas 55+ mg. of dextrinated azide were required. These
data were plotted as % fired vs. base charge.

Next the minimum quantity of priming necessary to
initiate the lead azide satisfactorily was determined hold-
ing the azide and base charge constant, at a value above
the minimum previously determined. It was found that as
little as 5 mg. of NOL No. 130 would give reliable initia-
tion of the system. This determination was made using the
assembly shown in Figure VI, Drawing A-3 which re-intro-
duced the problem of input energy now that initiator and
base charge had been removed from the area of suspicion.

The 100% firing values for charge weight were
then calculated in terms of inches of column height in the
detonator, and were plotted in terms of base charge vs.

BLK. PDR. FUZE
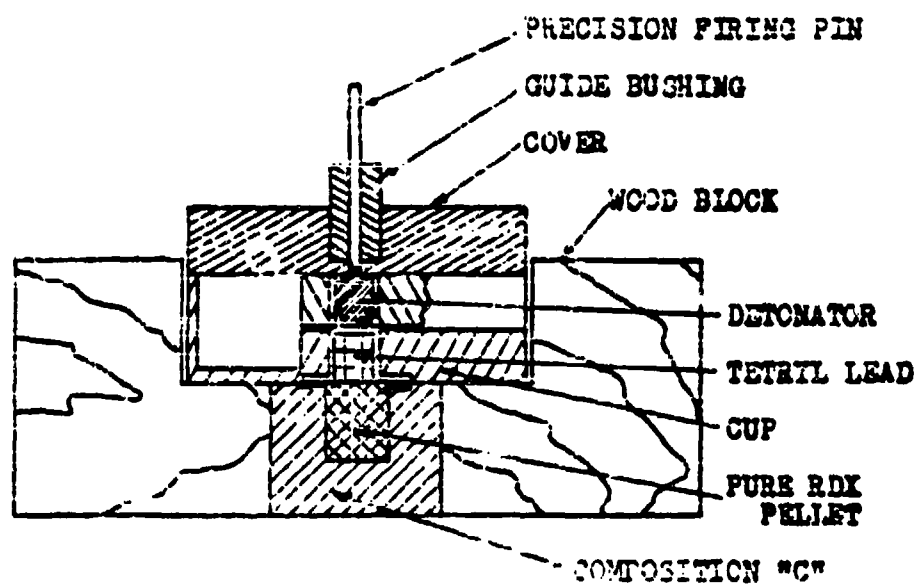
COVER

WOOD BLOCK

DETONATOR HOLDER

DETONATOR

TETRYL LEAD

CUP

RDX PELLET

COMPOSITION "C"

Test Assembly
(Without Priming)

Figure V   Drawing A-2

PRECISION FIRING PIN

GUIDE BUSHING

COVER

WOOD BLOCK

DETONATOR

TETRYL LEAD

CUP

PURE RDX
PELLET

COMPOSITION "C"

Test Assembly
(For complete primer - detonator)

Figure VI   Drawing A-3
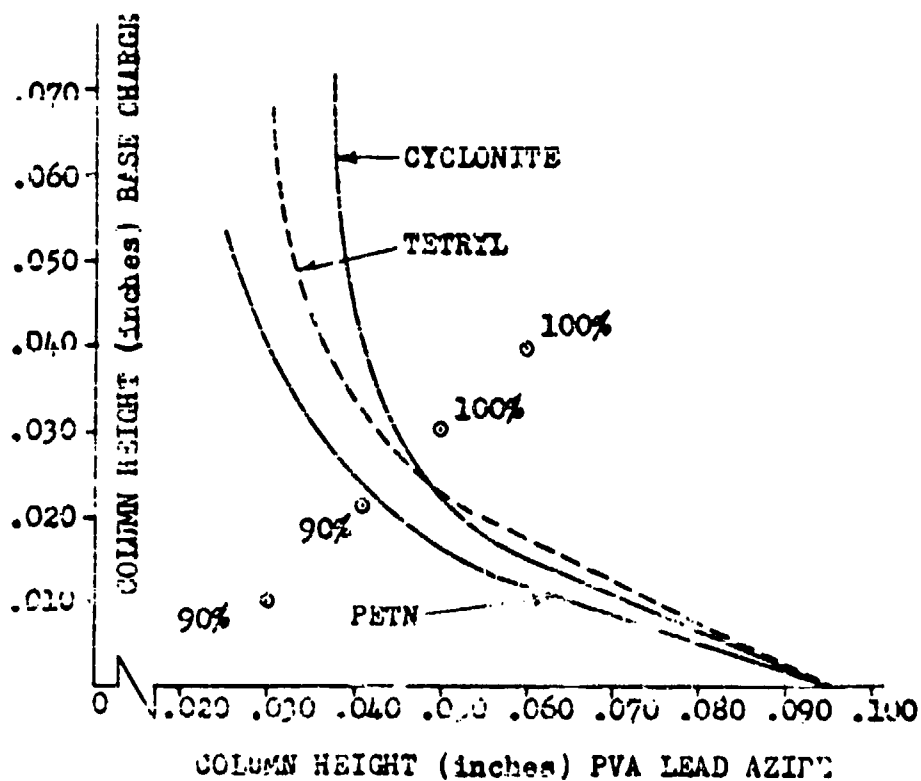
Confidential

100% FUNCTIONING CURVES

Base Charge Column Height vs. PVA Azide Column Height

VARIATION OF INITIATOR VS. BASE CHARGES FOR
100% FUNCTIONING WHEN TESTED AS IN SKETCH A-2

THE FOUR POINTS WERE ESTABLISHED IN TEST
ASSEMBLY A-3 WITH COMPLETE DETONATORS

Figure VII   Drawing A-1

initiator in inches. This gave the curves shown in Figure VII, Drawing A-1.

All of the potentially useful values for column height of initiator and base charge fall above the curves. The area below the curves gives unreliable functioning. A study of the tolerances experienced in production loading then permitted the selection of a point above the curves and yet within the total length of the detonator which would permit the normal variables in production (i.e., charging of lead azide and the base charge) without getting outside that useful area.

The final loading recommended for production was: Base Charge, Tetryl .010 grams, PVA Lead Azide .040 grams, and NOL No. 130 Priming .015 grams, permitting considerable safety margin, percentage-wise, on each charge, whereas the volume available did not permit an acceptable design using dextrinated lead azide.

Although not discussed above, it is interesting to note that a condition of dead pressing of tetryl was experienced in several of the experimental detonators in which the lead azide charge was marginal, such that a decrease in loading pressure from 25,000 p.s.i. to 15,000 p.s.i. caused an otherwise identical design to change from 100% failures to 100% high order detonations.

A number of fuze designs have been built around an electric detonator of about the size and input characteristics of the Mk 124 Primer. As its name implies, this item was not originally designed as a detonator. However, it has been found to function satisfactorily as a detonator under certain circumstances. These circumstances are not prevalent in all of the proposed designs, so that the problem arose of producing a detonator of the same dimensions but with greater effective output. One expedient which was suggested by S. Kolodny of the Diamond Ordnance Fuze Laboratories was that of inserting a steel washer at the beginning of the explosive column to increase the confinement and promote the growth of detonation. Another was the substitution of PVA for dextrinated lead azide.

Special detonators were fabricated from Mk 124 Primer parts. The detonators were divided into two groups, a confined group and an unconfined group. Each group had two series, one with dextrinated lead azide and the other with polyvinyl alcohol lead azide, as intermediate and flash charges, Figures VIII and IX. All four series had base charges of PETN. Members of each series were loaded with various amounts of lead azide and PETN and the output of each item was obtained using the dent test. (4)

CUP AND CHARGE
(64 MGS PETN; 10,000 PSI)

FERRULE CONTAINS
19 MGS PETN; 10,000 PSI

IGNITION CHARGE
(5 MGS MILLED DEXTRINATED
AZIDE; 2000 PSI)

← 0.115 → ← 0.060 → ← 0.180 →

0.360
± .010

Figure VIII

21 MGS PVA; 10,000 PSI

FERRULE   ← 0.02″ →   STEEL RING

ELECTRICAL INSULATOR

CUP AND CHARGE
(19 MGS PETN; 10,000 PSI)
(94 MGS PVA; 10,000 PSI)
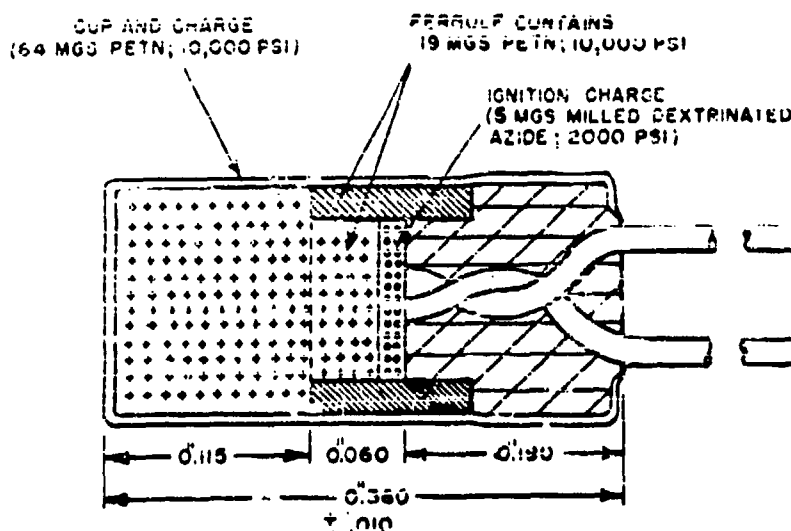
IGNITION CHARGE
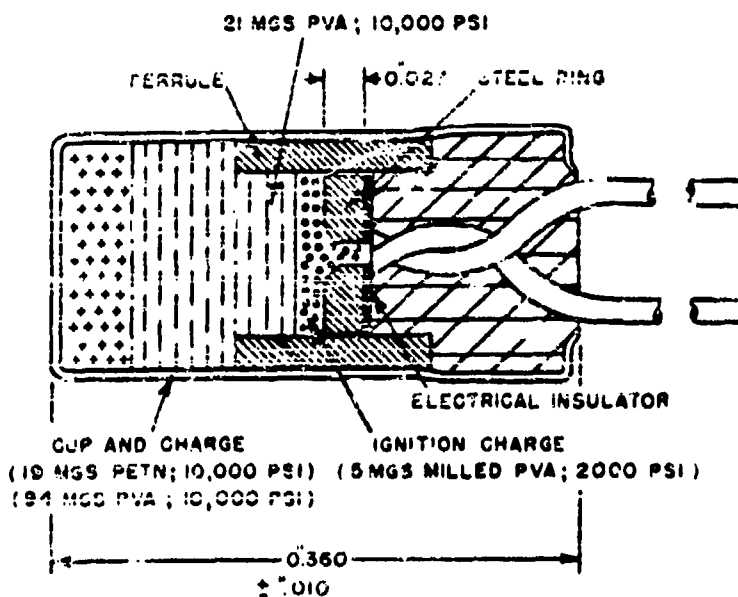(5 MGS MILLED PVA; 2000 PSI)

0.360
± .010

Figure IX

Confidential

The results are plotted in Figure X, next page. It will be noted that the dextrinated lead azide, unconfined, gave no measureable output when only five milligrams were used and that the maximum for this series was that with forty milligrams of lead azide. The effect of the confining disc upon the shorter columns of dextrinated lead azide is quite dramatic. In contrast, the PVA lead azide detonators without the confinement were more effective than those with it. In this case apparently, the principal effect of the steel washer was that of displacing some explosive.

Other Properties

The two outstanding features of PVA lead azide are (a) the ability of small charges to initiate RDX very efficiently and (b) its pressure density relationship is such that a quantity (by weight) of PVA lead azide can be pressed into a smaller volume than the same quantity of dextrinated lead azide consolidated at the same pressure. In very small detonators, this latter feature is almost as important as the former. The following table shows the pressure density relationship of dextrinated and PVA lead azide.

Pressure-Density Relationship of
Dextrinated and PVA Lead Azides

Pressure of Consolidation (p.s.i.)	Density gm./cc Dextrinated Lead Azide	PVA Lead Azide
3,000	2.62	3.31
6,000	2.88	3.51
9,000	3.27	3.55
12,000	3.08	3.69
15,000	3.14	3.81
20,000	3.27	3.8
25,000	3.30	3.84
30,000	3.34	3.94

Figure XI

The increased ability of PVA lead azide as an initiating explosive does not show up in the quantity of sand crushed in the so-called "brisance test". Six hundred milligrams of both types of lead azide crushed an average of approximately 25 grams of sand.

A third interesting feature of PVA lead azide is that it is practically non-hygroscopic. The moisture
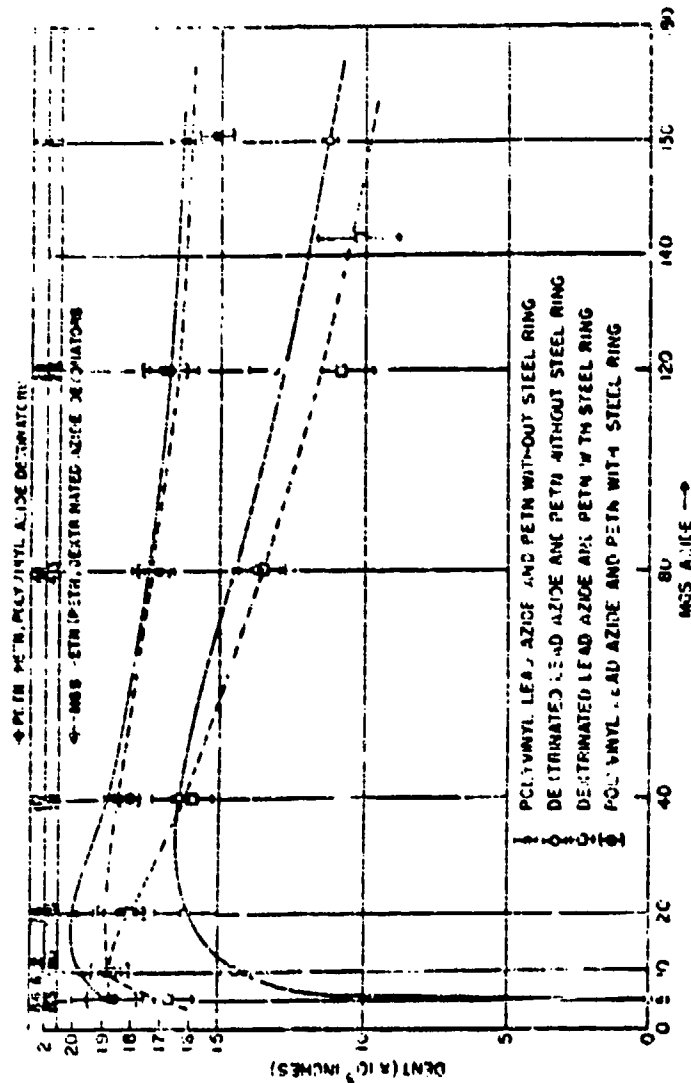
THE FIGURE OF DEPT TEST FOR AZIDE/PETN DETONATORS CONFINED AND UNCONFINED

Figure X

Confidential

picked up by a typical lot of dextrinated lead azide is as
follows:

Hygroscopicity of Dextrinated Lead Azide

Exposure Period (Hours)	% Increase in Weight of Dextrinated Lead Azide Exposed to 90% R. H. at 30° C.
1	0.55
2	0.54
3	0.64
4	0.64
5	0.68
6	0.71
7	0.71
24	1.00
28	1.05
48	1.16
120	1.17

Figure XII

By comparison PVA lead azide when exposed to 90%
R. H. and 21° C. picked up only 0.03% moisture before
coming to constant weight. It was found that moisture
content of the lead azide used in the T32 Detonator was
critical. When dextrinated lead azide containing more than
0.7% moisture was used, a large number of (low order)
failures of the detonator was experienced.

Results of stability tests indicate that PVA lead
azide is a stable explosive. Laboratory tests involving
the determination of weight lost and quantity of gas
evolved during prolonged heating show:

	#1	#2	Ave.
Loss in wt. on heating at 100° + 1°C. for 8 hours. (in duplicates),%.	0.14	0.10	0.12

	at 100°C.	at 120°C.
Quantity of gas evolved from 1 gram of sample during 40 hrs. (Vacuum stability test),ML	0.16	0.46

In addition, results of firing tests on modified
T32 Detonators containing PVA lead azide, as the initiat-
ing charge, during storage at 71°C. over a period of 12
months indicated that this explosive is stable and com-
patible with the other ingredients which make up the det-
onator.

At the present time the Ordnance Corps will per-
mit the use of PVA lead azide in explosive trains only

Blake, Seeger and Stresau

where it is not feasible to use dextrinated lead azide.
The restricted use of PVA lead azide is attributed to the
presence of log or lath shaped crystals having dimensions
as great as .4 mm. Pertaining to the sensitivity of lead
azide as a function of the crystal size, Tenny L. Davis
states that "The sensitivity of lead azide to shock and
friction increases rapidly as the size of the particle in-
creases. Crystals 1 mm. in length are liable to explode
spontaneously because of internal stresses within them."(5)
The Ordnance Corps to the present time has specified that
the lead azide to be used will contain no needle-like
crystals exceeding .1 mm. in length. Considerable amount
of work has been conducted to determine if the larger crys-
tals found in the PVA lead azide render this material un-
duly hazardous. To date no significant difference between
impact sensitivity of the standard lead azide and PVA lead
azide has been found, except where abrasive is present.

Several references, one in a recent issue of
Nature (6), however, state that the idea that large crys-
tals of lead azide are always excessively sensitive to
shock or friction has been widely received, but seems to
have little foundation.

Regarding the possible presence of the unstable
beta form crystals in PVA lead azide, X-ray diffraction
patterns of both the dextrinated and PVA lead azide were
obtained. Examination of these patterns indicated that
they were identical.

Figure XIII following presents data showing typi-
cal impact, stab and hot wire sensitivities for PVA lead
azide and dextrinated lead azide.

Discussion

The growth of detonation in most explosives in-
volves a period of burning, followed by a low velocity
detonation phase, and finally stable detonation. The out-
standing "priming efficiency" of lead azide among common
primary explosives is undoubtedly related to the extreme
rapidity with which it undergoes this process. The burn-
ing phase which is quite visible in streak camera photo-
graphs of incipient detonation of most explosives is not
generally observed in lead azide. (9)

This behavior has inspired the idea that the
mechanism of initiation of lead azide and explosives which
behave similarly is different from that of other explosives.
Garner (10) has proposed a mechanism involving a chain
reaction and has concluded that the decomposition of two

Confidential

adjacent molecules in a period of ten to the minus 13 seconds is sufficient to start a spherical wave of reaction which may develop into an explosion. He also concludes that the probability of this event in normal initiating conditions is sufficiently high to account for the

Figure XIII - Sensitivity

Impact	NOL No.	PVA Lead Azide Lab Sample X-105	PVA Lead Azide Plant Sample X-114	Dextrinated Lead Azide X-73	Dextrinated Lead Azide Lot 64
Type 3 tools (2.5 kg wt.) H (7)		36 cm.	55 cm.	33 cm.	
Type 12 tools* (500 gm. wt.) (8)			9 cm.	28 cm.(8)	20 cm.
Type 12 tools* (1 kg. wt.)			3 cm.	14 cm.(8)	8 cm.
Type 12 tools* (2.5 kg. wt.)			2 cm.	10 cm.(8)	4 cm.
Type 3 tools (2.5 kg. wt.) As a component of primer mix (7)			5 cm.	21 cm.	

Stab

As a component of a priming mix in Mk 102 primers		1.61 in.	2.25 in.	2.12 in.	
As a component of a priming mix in Mk 28 detonators		4.50 in.		4.63 in.	
As a component of a priming mix in Mk 44 detonators		2.3 in.		3.42 in.	
Hot wire 0.00027" dia. wire		1412 ergs		1288 ergs	
Hot wire 0.0001" dia. wire		222 ergs		257 ergs	

*In type 12 tools the explosive is placed on sandpaper

Confidential

initiation of lead azide. Bowden and Yoffe, (11) have expressed the opinion that lead azide may be initiated by tribochemical excitation. The hot spot mechanism of initiation, the broad applicability of which has been established by Bowden and various co-workers, (9), (11) and (12) may also apply to lead azide. The rapid acceleration of the action of this material may be the result of its high melting point and mechanical strength, both of which are conducive to the formation of hot spots.

The transition from a less vigorous reaction to detonation depends upon the acceleration of weaker reactions and the consequent development of strong shock waves. In all of these incipient reaction processes which have been proposed as peculiar to lead azide and similar explosives as well as the more common incipient burning, the condition of the surfaces of the grains and crystals is important. A coating of a foreign material can serve as a barrier to retard the propagation of burning or chain reactions or as a cushion and lubricant to reduce crystalline stresses and inter-crystalline friction. The effect of an impurity upon the propagation rates and acceleration of such reactions may be much greater than would be predicted on the basis of dilution, and may be expected to depend strongly upon the nature of its distribution as well as its properties and concentration.

Each individual grain of dextrinated lead azide is an agglomerate of perhaps a million crystallites, Figure I, while each particle of PVA lead azide is an individual crystal, usually several times as long as it is wide, Figure I. It is inconceivable that PVA lead azide could be consolidated by pressure without breaking many crystals and exposing a large number of clean surfaces. The consolidation of dextrinated lead azide by redistribution of the crystallites within a dextrin matrix would appear possible. The existence of clean surfaces of explosive could be very conducive to the operation of some of the propagation processes mentioned above, and might help to explain some of the differences in performance between dextrinated and PVA lead azide reported above. Detonation may be defined as a self propagating explosive reaction in which the controlling mechanism whereby energy is transmitted from the reacted to the unreacted explosive is that of a hydrodynamic shock. The parameters of stable detonation, including its propagation velocity, are determined by equilibrium conditions at the end of the reaction zone, in which the losses of material exactly balance the influx due to the propagation of the wave into virgin explosive and the losses of energy exactly balance the sum of the thermal and available chemical energy of the unreacted material overtaken. These conditions are affected by the

reaction rate only to the extent that it affects the geometry of the reaction zone and the consequent deviation from one dimensional flow in this region. The design of most explosive components is such that this deviation is quite small. The acceleration of detonation from a lower rate to the stable rate requires an increase in pressure in the reaction zone, and depends upon the rate of this increase. In turn, increase in pressure depends upon the excess of either the material influx, the energy liberated by the reaction, or both over the losses from the reaction zone. The growth of detonation may be expected to be closely dependent upon the reaction rate.

The surface burning model has been shown to explain observable phenomena associated with the detonation of solid explosives. (13) Detonation of various explosives, including lead azide (14), has been observed wherein the propagation rate is so low that the temperature necessary for rapid reaction is attainable only by concentrating the heat of compression at "hot spots". Whether the hot spots result from intercrystalline friction or compressive heating of interstitial gases, the presence of voids* is important in the formation of hot spots. As the percentage of voids is decreased either by filling them with another material or loading the explosive at a higher density, its structure becomes more rigid and the shock pressure necessary to disrupt it becomes greater. Failure of the structure, of course, is necessary for either intercrystalline friction or appreciable compression of the gases. Thus, the propagation and acceleration of weak detonation is directly related to the proportion of voids in the material through which it is propagating. (13)

The rapid acceleration of detonation in lead azide may be attributable to the fact that under normal loading conditions, loading pressures between ten and twenty thousand pounds per square inch, a charge usually contains more than twenty percent voids. In considering the effect of organic impurities upon lead azide, the large density difference must be kept in mind. The eight percent by weight of impurities which is typical of dextrinated lead azide furnished under United States military specifications (1) would amount to over twenty-seven percent by volume, if it were all dextrin, and would reduce the voidless density to 3.7 grams per cubic centimeter as compared with 4.8 for pure lead azide. What might seem a small weight percentage of organic impurities may be expected to have a considerable effect upon the rate at which stable detonation is approached in lead azide.

The term "void" is used here in the sense of the absence of liquid or solid material. The presence of gases is, of course, necessary for one of the mechanisms proposed.

Confidential

Whether the initiation and growth of stable deto-
nation in lead azide is a process similar to but faster
than that in other explosives or a unique process, the time
and material expended in the process can be expected to be
influenced by impurities, particularly if the impurities
coat the particles of lead azide.

Measurements of the Detonation Properties of PVA and Dextrinated Lead Azide

The velocities of both PVA lead azide and dextri-
nated lead azide were measured for columns 0.2 inches in
diameter heavily confined in brass. Each velocity was
measured over the second inch of a two inch long column.
The results are given in Figure XIV.

Pressure-Density-Velocity Relationship of Dextrinated and PVA Lead Azide*

Loading Pressure p.s.i.	PVA Lead Azide		Dextrinated Lead Azide	
	Density gm./cc.	Det. Vel. m/sec.	Density gm./cc.	Det. Vel. m/sec.
4,000	2.99	4060	2.60	3800
16,000	3.45	4620	2.96	4130
32,000	3.77	4930	3.35	4400
64,000	3.85	5440	3.57	4880

Figure XIV

Note that for equivalent loading pressures the
detonation velocity of PVA lead azide is substantially
higher than that of dextrinated lead azide, but that, for
equivalent densities the dextrinated material detonates at
a slightly higher velocity. An increased detonation vel-
ocity for given density with the addition of a diluent to
an explosive may be expected where the decomposition pro-
ducts of the diluent have lower average molecular weights
than those of the explosive. Some investigators (15) have
observed slightly higher detonation velocities in Composi-
tion A than in RDX for equal densities. In the manufact-
ure of detonators, the density is limited by the loading
pressure which can be used, so that the velocity attain-
able with a given loading pressure is of more significance.
Since the shock pressure associated with a detonation is
nearly proportional to the product of the density and the
square of the detonation velocity, the detonation pressure
of PVA lead azide which has been pressed at 16,000 p.s.i.
is about half again as large as that of dextrinated lead

*Differences in values in Fig. XI and XIV are in line with
variations in unpressed density and loading components.

azide loaded at the same pressure. This difference is substantial, but not sufficient to account for all of the difference in performance which has been observed between lead azide manufactured by the two processes.

The possible influence of impurities upon the rate of growth of detonation in lead azide has been discussed. An experiment which may be considered to be evidence of a difference between the two types of lead azide involves the measurement of functioning times of electric detonators. Two groups of detonators were made which were similar except that the flash charge, that charge in direct contact with the bridge wire, was dextrinated lead azide in one case and PVA lead azide in the other. These detonators were fired by the discharge of a 0.2 mfd. condensor charged to various voltages. The functioning times were measured by means of the vacuum thermocouple timer.(16) The results are given in Figure XV.

Functioning Times of Detonators

	Flash Charge Material	
	Dextrinated	PVA
Firing Voltage	Lead Azide	Lead Azide
(Volts)	(Microseconds)	(Microseconds)
40	4.0 - 8.0*	1.95 - 2.4*
140	3.8 - 3.12	1.45 - 1.9
350	2.5 - 3.05	1.45 - 1.75
700	2.15 - 2.68	1.25 - 1.75
1400	1.50 - 2.55	1.28 - 1.45
2800	1.56 - 2.02	1.38 - 1.50

* Spread of four to eight measurements.

Figure XV

It will be noted that the detonators with PVA lead azide functioned more rapidly at each voltage and that the dextrinated lead azide showed a progressive decrease in functioning time with increasing voltage while the PVA lead azide changed hardly at all except at the lowest voltage used. Taken by itself, this data might be taken to indicate that the detonators loaded with PVA lead azide were much more sensitive. Measurements of the minimum firing energy, however, fail to bear this out. The energy required for fifty percent firing of the detonators with the dextrinated lead azide flash charges was found to be about 1500 ergs and that for the PVA lead azide 1400 ergs. This difference in energy requirement is not statistically significant. Note that the energy used in the time experiments ranged from 1600 ergs up. The difference in the

Confidential

times must be attributed to the difference in the rate of
growth of detonation in the two materials. The measured
functioning times for the PVA lead azide are quite close
to the time which a detonation might be expected to re-
quire to traverse the distance between the bridge wire and
the probe used to detect functioning of the detonators.
The difference in functioning time between the PVA and
dextrinated lead azides is obviously much more than can be
accounted for on the basis of the difference in their
stable detonation rates.

If this time data are considered in conjunction
with the output data of Figure X, it becomes quite appar-
ent that an important difference between PVA lead azide and
dextrinated lead azide is in the rapidity with which they
grow to detonation. The lack of any improvement in the PVA
lead azide results can be considered evidence that this
material builds up to stable detonation so rapidly that
little is to be gained by confinement of this kind.

Conclusions

From the foregoing, it may be concluded that:
Dextrinated lead azide grows to detonation more slowly
than PVA lead azide.

A significant quantity of explosive is expended
in this growth process. The explosive consumed in the
growth of detonation is less effective in initiating the
subsequent charge than that which detonates at the stable
rate. For these reasons, and because it can be consoli-
dated at higher densities, PVA lead azide is appreciably
more effective as an initiator, particularly where space
is at a premium.

Confidential

Blake, Seeger and Stresau

References:

(1) Military Specification for Lead Azide, MIL-L-3055, 30 September 1949, Amendment 1, 24 March 1952

(2) British Service Azide Specification IG237, A 163 E

(3) U. S. Patent 2,421,778

(4) NAVORD Report 2815 Direct Initiation of Boosters, by R. H. Stresau, W. M. Slie and L. D. Hampton

(5) The Chemistry of Powder and Explosives, by Tenny L. Davis

(6) Nature, 172 (Aug. 29) p. 379, 1953, Size Effects in the Initiation and Growth of Explosions by F. P. Bowden and K. Singh

(7) NAVORD Report 1589, N. D. Mason, Impact Sensitivity Determinations of Explosive Compounds Tested During the Period from 1 January 1950 to 1 November 1950

(8) NAVORD Report 2111, George Svadeba, Impact Sensitivity of Primary Explosives, 1 June 1951

(9) F. P. Bowden and A. D. Yoffe, The Initiation and Growth of Explosions in Liquids and Solids, Cambridge University Press, 1952.

(10) W. E. Garner, Transactions of the Faraday Society, 34, 985, 1008, 1938.

(11) F. P. Bowden and A. D. Yoffe, Research 1, 581, 1948

(12) F. P. Bowden and O. A. Gurton, Proc. Roy. Soc. A, 1958, 337, 350, 1949

(13) H. Eyring, R. E. Powell, G. H. Duffey, and R. B Parlin, Chem. Rev. 45, 69, 1949

(14) R. H. Stresau, NAVORD Report 2460, 28 May 1952

(15) L. D. Hampton, NAVORD Report 3731, September, 1954

(16) R. H. Stresau and C. Goode, NAVORD Report 2137, 29 June 1951

THERMO-HYDRODYNAMICS AND REACTION KINETICS IN SOME
METALIZED EXPLOSIVES

Melvin A. Cook, Aaron S. Filler, Robert T. Keyes
William S. Partridge, and Wayne O. Ursenbach
University of Utah
Salt Lake City, Utah

ABSTRACT

Experimental velocity-diameter curves are presented for 80/20 TNT-AN, 45/30/25 HBX-TNT-l, 75/25 HBX, various mixtures of AN-Al ranging from pure ammonium nitrate to 60 percent AN, RDX, and 95/5 RDX-boron. Velocity-density relations are presented for all except the last two explosives. Wave shape vs. diameter measurements for the aluminized explosives are also summarized.

Results show that the Al reacts too rapidly for rate to be a real limiting factor in TNT and RDX-Al mixtures, but relatively slowly in the AN-Al mixtures. The familiar properties of the high temperature Al explosives are attributed to the thermodynamics of Al reactions in which the $Al_2O(g)/Al_2O_3(c)$ ratio is appreciable in the detonation wave and negligible as far as the maximum available work integral $A = \int p \, dv$ is concerned. The change of this ratio from a high value in the detonation wave to a low one later on gives aluminized explosives low "brisance" but high blast potential. Preliminary results suggest a similar effect for boron.

The AN-Al mixtures were shown to be non-ideal over the entire range of conditions studied. Reaction rates in these mixtures depend on the particle size of both the AN and the Al. They seem to be controlled by mass transfer which leads to anomalous $D(\rho_1)$ curves showing a maximum at a relatively low density around 1.0 to 1.2 g/cc.

INTRODUCTION

The studies summarized in this article represent investigations described in three technical reports (1,2,3) on this project in addition to work not previously reported on the variation of velocity with density in AN-Al and AN-TNT and preliminary velocity vs. diameter results for 95/5 RDX-boron. The studies of aluminized explosives

include rather complete investigations with 80/20 TNT-Al, 45/30/25
RDX-TNT-Al, and 75/25 HBX together with various mixtures of ammonium
nitrate (AN) and aluminum ranging from zero to 40 percent Al.

Aluminized explosives are characterized in general by rela-
tively low "brisance" but high (underwater, open air and underground)
blast potential. The low relative "brisance" of aluminized explosives
has been attributed in the past to incomplete reaction of Al at the
C-J plane and the high blast potential to after burning of aluminum.
Early shaped charge studies with torpex and other aluminized explosives
interpreted in light of the observed linear variation of hole volumes
produced in uniform targets with detonation pressure in charges of con-
stant geometry and constant cones using C-H-N-O explosives where deto-
nation pressures could be computed unambiguously,(A) indicated that
aluminum acted effectively as a diluent as far as shaped charges are
concerned. More careful studies of this nature carried out in this
laboratory showed, however, that the effective (or 'measured') detona-
tion pressures in some aluminized explosives were even considerably
lower than one can account for by mere dilution with an inert additive.
Moreover, extensive velocity-diameter studies showed that aluminum re-
acts very rapidly in tritonal and HBX, diameter effects disappearing
in relatively small diameters. These results described below brought
out that an explanation of the behavior of aluminum in tritonal and
HBX was to be found not in the kinetics of reaction of aluminum but in
the thermodynamics of aluminum reactions.

A careful study of the thermodynamics of various aluminum
products was therefore carried out and results showed that the possible
detonation products of aluminum in C-H-N-O explosives were $Al_2O(g)$,
$AlO(g)$ and $Al_2O_3(c)$, (g = gas, c = condensed). Approximate constants
were computed from statistical mechanics from which the distribution
of aluminum in these three products could be computed approximately by
including these equilibrium constants along with others applicable in
C-H-N-O explosives in the computation of the thermo-hydrodynamics of
aluminized explosives. Al_2O_3 apparently does not exist in the vapor
phase. (Later computations showed that AlO is also unimportant at
least at low oxygen balance.) The results of the thermo-hydrodynamic
calculations incorporating these equilibrium constants for tritonal
and HBX were very enlightening; they showed that the ratio $Al_2O(g)/$
$Al_2O_3(c)$ was large at low densities and did not reach zero even at the
maximum possible densities. Moreover, by reference to the empirical
(universal) $\alpha(v)$ curve, it became evident that the velocity-density
curves of TNT-Al and RDX-TNT-Al mixtures should not be linear as in
normal C-H-N-O explosives but should show considerable curvature. This
prediction was later verified by velocity D vs. density ρ_1 measurements
in these explosives. The results of these studies therefore appeared
to give a satisfactory explanation of the characteristic behavior of
the aluminized explosives HBX and tritonal, presented later in the
discussion.

It was expected that the situation would be somewhat differ-
ent in explosives of higher oxygen balance. To study the aluminum

115

reactions in detonation at high oxygen balances therefore various AN-Al mixtures were studied. Thermo-hydrodynamic calculations in this case showed that the ratio $Al_2O(g)/Al_2O_3(c)$ should be negligible up to 15 percent Al, owing to the relatively low temperature of these mixtures. While it was expected that AlO would become important, contrary to expectation the calculated ratio $AlO(g)/Al_2O(g)$ proved negligible even at the highest oxygen balances studied. However, this result remains uncertain since the calculated equilibrium constants may not be sufficiently reliable to insure the accuracy of this conclusion. While the rate of reaction of Al in tritonal and HBX was relatively high, it was relatively slow in the AN-Al mixtures. Indeed, the properties of these mixtures were found to depend critically on the rates of reaction of both AN and Al. Sample thermo-hydrodynamic calculations for the above three series of explosives are given in Table I.

While Al has great practical importance, other metals are also of considerable interest in explosives. Studies of metallized explosives being carried out at the present time thus have as their objective the elucidation of the behavior of these metals also. To date only preliminary studies of boron in RDX have been carried out and are summarized here.

The experimental results obtained in the above studies are summarized in this article together with a discussion of the behavior of aluminum and boron in the explosives studied. In addition to the velocity-diameter $(D(d))$ and velocity-density $(D(\rho_1))$ studies carried out in connection with determinations of the reaction rates and thermo-hydrodynamics of the aluminized explosives, extensive measurements of wave shape were also carried out. These results are also summarized in this article.

EXPERIMENTAL

D(d) Curves for Tritonal and HBX

Velocity-diameter studies of cast and loose-packed 80/20 TNT-Al, cast 75/25 HBX, and loose-packed 45/30/25 RDX-TNT-Al are presented in Fig. 1. Velocities were measured in these and other cases described here by pin oscillograph (5) and rotating mirror camera methods. (6) The charges all had a length/diameter (L/d) ratio of six or more. They were contained in thin-walled (larger diameters) or plastic tubes (smallest diameters). Densities were measured in samples of the cast charges by sectioning them. They were found to show some axial and radial density fluctuations limited in all cases, however, to two percent or less. The loose-packed charges were vibrated for density uniformity, care being taken to avoid segregation by excessive vibration. Densities were determined in all cases by total weight/total volume measurements. Velocities were corrected to an average density in each case by appropriate $D(\rho_1)$ relations.

Cook, Filler, Keyes,
Partridge, Urizenbach

No systematic aluminum particle size or diameter effects were found in either the 80/20 TNT-Al or 45/30/25 RDX-TNT-Al except for the former at diameters less than 5 cm. In fact in the HBX series no definite diameter or particle sizes effects were observed even in the lowest diameters studied. These results show clearly that the reaction rate of aluminum is not a limiting factor in the behavior of tritonal and HBX.

Of particular interest are the following comparisons:

Explosive	ρ_1	D(m/sec)
TNT	1.59	6910
80/20 TNT-Salt	1.75	6900
80/20 TNT-Al	1.75	5800
TNT	0.85	4525
80/20 TNT-Salt	1.00	4400
80/20 TNT-Al	1.00	3840
60/40 RDX-TNT	1.70	7800
45/30/25 RDX-TNT-Salt	1.77	(7430)*
45/30/25 RDX-TNT-Al	1.77	7200
60/40 RDX-TNT	1.00	(5650)*
45/30/25 RDX-TNT-Salt	1.15	(5400)*
45/30/25 RDX-TNT-Al	1.15	4600

*By linear interpolation of results for TNT-salt and RDX-salt mixtures.

These results show that aluminum lowers the velocity of TNT, 60/40 RDX-TNT and composition B more than salt which acts (if not as a pure diluent) as a slightly heat absorbing solid. Clearly, therefore, aluminum must have a strongly endothermic effect at the C-J plane. This would be the result if $Al_2O(g)$ were to form in appreciable amounts. But if $Al_2O_3(c)$ were to become the sole aluminum product, the large diameter velocity of the TNT-Al and RDX-TNT-Al mixtures would have been appreciably higher (even at the same density) than the velocity in the corresponding explosives without aluminum.

The effectively endothermic reaction of Al in the detonation wave may be seen also in the following results of detonation pressure measurements by the shaped charge method.(8)

Explosive	ρ_1	p_2(atm x 10^{-3})*
TNT	1.59	150
80/20 TNT-Al	1.68	140
TNT	0.81	45
80/20 TNT-Al	0.94	45
Composition B	1.71	230
80/20 HBX	1.81	170
73.2/26.8 HBX	1.83	155

*Average deviation from mean 5-10 percent.

Thus the actual detonation pressures of tritonal and HBX were less.

than in TNT and composition B even though the densities of the former explosives were 6 to 8 percent higher ($\rho_o = \rho_1$ IW $\approx \rho_1 D^2/4$). The density increase was not enough except in the low density TNT-Al, however, to make up for the endothermic reaction.

$D(\rho_1)$ Curves for Tritonal and HBX

Thermo-hydrodynamic calculations for tritonal and HBX using a linear $D(\rho_1)$ curve and the new Al-distribution equilibrium constants in the inverse solution method (9) gave inconsistent results. (The values of D_2 were too large and the computed $\alpha(v)$ curve deviated considerably from the 'universal' one.(10)) These results suggested, therefore, that the $D(\rho_1)$ curve should not be linear. Measurements of the $D(\rho_1)$ curves for pressed 80/20 TNT-Al in 8.5 cm (L/d = 6) charges and for 45/30/25 RDX-TNT-Al at d = 5.2 cm and L/d $\geq$ 6 were therefore carried out. These diameters were chosen to insure ideal detonation. The results are shown in Fig 2. The $\alpha(v)$ curves calculated using the observed $D(\rho_1)$ curves were in much better agreement with the 'universal' curve and the calculated pressures were also in much better agreement with the observed ones. There remained a discrepancy in the $\alpha(v)$ curve for tritonal, although the calculated pressures were in good agreement with the observed ones in this case. For HBX the computed $\alpha(v)$ curve was in excellent agreement with the 'universal' curve, but the calculated pressure at high density was still about 25 percent too high. However, this discrepancy was of the order of magnitude associated with the limits of uncertainty in the equilibrium constants determining the $Al_2O(g)/Al_2O_3(c)$ ratio.

$D(d)$ Curves for AN-Al Mixtures

Experimental $D(d)$ and D vs. percent Al (constant d) data for AN-Al mixtures varying in composition from 100/0 to 70/30 are shown in Fig 3 and 4. The influence of Al particle size is also indicated by some of the results shown in Fig. 5 for 8 to 20 percent Al. Additional data showing Al particle size effects are given in Tables II and III. The AN-Al mixtures were all non-ideal at velocities far below the ideal velocities in all cases irrespective of the particle size of either the AN or Al. No attempt was made to correct velocities for small density fluctuations owing to the anomalous $D(\rho_1)$ relations noted in Fig. 3. For example, the velocity was in general considerably lower on the high density side than on the low density side. Previous unpublished studies have shown that this is a characteristic of fuel or combustible sensitized AN explosives at D/D^* considerably less than unity.

In order to show the anomalous density effect unambiguously, $D(\rho_1)$ measurements were carried out with the 90/10 AN-Al mixture using a single uniform unscreened Al sample throughout. These results are shown in Table IV. In the first series using a fine AN product (sample 1, Table IV), the $D(\rho_1)$ curve was found to go through a maximum somewhere between a density of 1.09 and 1.28. These measurements were repeated about three weeks later using the same lot of AN. However, clearly this sample had changed during the three week interval, as

noted, for example, by the fact that it packed to a lower density. In this series the maximum velocity (3485 m/sec) was observed at about $\rho_1 = 1.12$ and the velocity was 950 m/sec lower at $\rho_1 = 1.25$ than at $\rho_1 = 1.12$. Pressing crushes the AN somewhat, hence the anomalous $D(\rho_1)$ effect should be even more pronounced than indicated by these two series (AN samples 1 and 2, Table IV). To show the real $D(\rho_1)$ effect, one s should use constant particle size. To accomplish this, several shots were made in which the pressed charges were compared with loose-packed ones made by first pressing the AN to the density of the corresponding pressed charge, crushing the mixture and loose packing it in charges of the same diameter and length. Three comparisons of this sort are shown in Table IV (AN samples 3, 4, and 5). Note that the low density product showed a higher velocity than the higher density one, and the difference increased with the density difference. These results show that the $D(\rho_1)$ curve for 90/10 AN-Al with fine AN and fine Al exhibits a maximum at some value of density below $\rho_1 = 1.25$. Another more easily reproducible example of the anomalous $D(\rho_1)$ effect in AN explosives is shown in Table IV for a 90/10 AN-DNT mixture using liquid DNT and fine AN. Again the $D(\rho_1)$ curve is shown to go through a maximum in this case near $\rho_1 = 1.18$ g/cc.

The AN-Al mixtures are complicated non-ideal explosives; besides the anomalous $D(\rho_1)$ relations, particle size effects may be observed not only in Al but also in AN. The AN particle size was not allowed to vary more than the amount caused by crystal growth in the AN and the ability to reproduce particle size in AN from one lot to another. As a result, no definite particle size effects of AN were noted. To show that the AN particle size also influences velocity in these mixtures, therefore, two shots were made in 10 cm diameter charges using a much coarser AN product and the same grade of aluminum as in the comparative examples. The results (AN sample 6 in Table IV) showed an average velocity about 1000 m/sec lower than for the finer grade AN charges of the same density and Al particle size.

D(d) Curves for RDX and 95/5 RDX-Boron

A preliminary (partial) D(d) curve for loose-packed 95/5 RDX-boron is compared with the D(d) curve for RDX in Fig. 5. The RDX used in both cases was 65 to 100 mesh. The boron was a sample of quality still to be determined. These results are as yet too meager to allow reliable conclusions to be made, but they indicate that the reaction at the C-J plane for boron as for aluminum may also be an endothermic one relative to the products of detonation of RDX. Note, for example, that the reaction rate of RDX seems to be considerably retarded in the mixture indicating a considerable drop in detonation temperature. For diameters above 1 cm, RDX appears to detonate with ideal velocity $(D/D^* = 1.0)$. However, the results for the 95/5 RDX-B mixture showed D still to be increasing even at $d = 7.5$ cm. At $d = 1.3$ cm the velocity of the mixture was about 10 percent lower than for pure RDX, and at $d = 7.5$ cm it was about 5 percent lower. If B were a pure diluent, the ratio of the D^*'s for the two explosives would be about 0.975.

Confidential

Wave Shape Measurements in Aluminized Explosives

After considerable effort to obtain quantitative wave shape results in cast tritonal and HBX, studies were discontinued owing to the very erratic results obtained. The cause of these irreproducible results was not only the difficulties inherent in casting such mixtures, but also a tendency toward segregation of the aluminum causing it to concentrate along the charge axis enough to attenuate the wave at this position more than toward the sides. Apparently relatively slight segregation of this sort is sufficient to flatten and even invert the wave from its normal value for an homogeneous charge. The effect of Al segregation is much more pronounced than density fluctuations along the charge axis which also tends to flatten or distort the wave.

In the loose-packed and pressed charges of 80/20 TNT-Al and 45/30/25 RDX-TNT-Al, the wave shapes showed normal reproducibility and normal curvature. The waves were spherical in shape and showed a constant or steady state value R_m at large L/d. Values of R_m/d obtained for the loose-packed mixtures of TNT-Al and RDX-TNT-Al with two grades of Al (-325 mesh and 65 to 100 mesh) are plotted against diameter in Fig. 6. R_m/d vs. ρ_1 curves for pressed 80/20 TNT-Al and 45/30/25 RDX-TNT-Al obtained at d = 8.5 cm and d = 5.2 cm, respectively, are shown in Fig. 6. R_m/d increased for TNT-Al from 1.45 at $\rho_1 = 1.0$ to 2.5 at $\rho_1 = 1.56$ at which density the R_m/d vs. ρ_1 curve still had a fairly steep slope. In the RDX-TNT-Al mixture, however, R_m/d increased from 1.95 at $\rho_1 = 1.18$ to the limiting value of about 4.0 at $\rho_1 = 1.48$. This mixture showed no further increase in R_m/d with density as the wave increase from $\rho_1 = 1.48$ to 1.57, the average limiting value of R_m/d being 3.85.

Wave shape data obtained for the AN-Al mixtures are given in Table V. They show R_m/d to be confined to the relatively narrow range between 0.9 and 1.7 in the diameters studied.

DISCUSSION OF RESULTS

Temperatures and pressures at the C-J plane for low density TNT-Al and RDX-TNT-Al mixtures are such that the chief product of aluminum is $Al_2O(g)$. This forms endothermically with respect to the products of detonation of these explosives and as a result the intensity of the detonation wave is reduced by aluminum. Owing to the much more rapid increase of pressure than temperature with density, however, the ratio $Al_2O(g)/Al_2O_3(c)$ decreases with density but remains appreciable even at the maximum density. As a result the influence of the highly exothermic product $Al_2O_3(c)$ never is sufficient in tritonal and HBX to overcome the endothermic effect of $Al_2O(g)$ at the C-J plane. The detonation velocities and detonation pressures (and "brisance") of these high temperature aluminized explosives are thus always lower than those of the corresponding explosives without aluminum even at the maximum densities, despite a 6 to 8 percent higher density for the aluminized explosive.

Confidential

The ratio $Al_2O(g)/Al_2O_3$ falls to zero at temperatures below about 3500°K at the "explosion pressures" p_3 of the high density aluminized explosives or below about 3000°K at very low pressures. This effect will, therefore, cause the temperature to be buffered at a value between 3000 and 3500°K during adiabatic expansion. The maximum available energy or total blast potential is determined by the integral

$$A = \int_{v_3}^{v_4} p\,dv = Q - q \tag{1}$$

where A is the maximum available work in expansion of the products of detonation from specific volume v_3 to v_4. Q is the heat of explosion and q is the heat retained by the products of detonation at v_4. In general detonations are very efficient in utilizing Q in work processes as long as the resistance of the burden is adequate. In open air blasts the resistance is low such that $A/Q \sim 0.15$ to 0.2, but in underground and underwater $A/Q \sim 0.8$ to 1.0 depending on the explosive. In either case, however, the buffering action of the ratio $Al_2O(g)/Al_2O_3$ (c) on temperature will tend to increase Q and A in aluminized explosives approaching as far as maximum available energy is concerned, the high value corresponding to zero in this ratio. Only where v_4 is effectively only slightly greater than v_3, as in applications requiring high brisance (e.g., shaped charge phenomena including impulsive loading of targets, cavity effect, etc.) will the high $Al_2O(g)/Al_2O_3$(c) ratios applicable in the wave front of detonation be important in lowering intensity. In cases where v_4 is effectively much greater than v_3, this ratio should be effectively zero. The thermodynamics of the $Al_2O(g)/Al_2O_3$(c) ratio thus appears to give a complete qualitative explanation of the behavior of the important high temperature, aluminized explosives. Quantitative computation should be possible for any particular set of conditions.

The situation is somewhat different in AN-Al mixtures. In the first place these mixtures have low enough detonation pressures and sufficient oxygen at Al < 15 percent that the $Al_2O(g)/Al_2O_3$(c) ratio is practically zero in this range. At 20 percent Al, where the explosive is approximately oxygen balanced, this ratio is still quite low and Q for detonation conditions is a maximum (at 1405 kcal/kg) since the ratio $Al_2O(g)/Al_2O_3$(c) increases rapidly as Al is further increased owing to the rapidly increasing temperature. However, A (in work processes where v_4 is effectively much greater than v_3) should continue to increase with percent aluminum in the AN-Al mixtures, perhaps to as high as 35 to 40 percent Al. The AN-Al explosives in this composition range should thus be very powerful ones for underwater, airblast, and underground use. However, while they should develop sustained pressures their peak pressures under all circumstances should be very low, particularly in small sizes where the D/D^* ratio is low.

Finally, let us consider briefly the kinetics of the reactions of AN-Al and AN-DNT mixtures in detonation. In previous studies of non-ideal explosives, including both pure explosives and mixtures, the surface burning (two-thirds order) rate law described by Eyring,

Confidential

et al.(12) was found to apply. The explosive mixtures studied, however,
were of a type in which the temperature generated by the reaction of at
least one of the ingredients alone without mixing would raise the tem-
perature in the products to near or even above the final equilibrium
temperature after thermodynamic equilibrium of the products. In AN-Al
mixtures, however, the temperature attained by reaction of AN alone
cannot exceed about 1700°K, whereas that for the complete mixture rises
much higher. Hence mass transfer and possibly heat transfer are much
more important factors in these mixtures than in a mixture such as
TNT-Al. The latter temperature in the gaseous phase will always be in
the neighborhood of the final temperature, but this is by no means true
in the mixture. Two other possible limiting factors besides heat trans-
fer in the condensed phases thus arise. The limiting factor deter-
mining rate in the AN-Al mixtures might be either (1) mass transfer
in the gas phase or (2) heat transfer in the gas phase.

In the previous examples studied these processes are appar-
ently unimportant and the rate of reaction is limited by the upper
limit of temperature and reaction rate in the solid (the Eyring pro-
cess). However, in AN-Al mixtures apparently the gaseous phase is
effectively not in equilibrium, and factor (1),(2) or both thus limit
the rate of reaction. The fact that the rate decreases rapidly with
density indicates that the limiting factor is mass transfer. (Diffu-
sion falls rapidly with increasing density or pressure in the vapor
phase, but thermal conductivity does not.) This situation corresponds
approximately to that occurring in granular "low" explosives such as
black powder in which the burning rate decreases with increasing den-
sity.

Single and double-base propellants in which the solid phase
is homogeneous have apparently thermal conductivity as the rate deter-
mining factor. That is, apparently the rate in these explosives is
determined by the temperature at the solid-vapor interface, but the
initial process of decomposition is endothermic or much less exother-
mic than the overall reaction. Most of the heat is thus generated a
short distance away from solid-vapor interface and must be transferred
back to support the reaction. The temperature gradient away from the
surface (temperature being smallest at the solid surface) therefore
increases with pressure, and the effective surface temperature also
increases with pressure. The result is that the burning rate increases
with pressure.

The anomalous $D(\rho_1)$ curves observed at d = 10 cm in 90/10
AN-TNT are believed characteristic of AN-combustible mixtures in small
diameters.

Quantitative studies of the D/D* vs. ρ_1 curves of such mix-
tures by means of the detonation head model should thus provide the
necessary reaction rate data for the study of their reaction kinetics.
It is possible that such studies would lead to valuable information on
mass transfer in gases at high densities and pressures in addition to
important practical and theoretical information on the reaction kinet-
ics of AN-combustible mixtures.

Confidential

Cook, Filler, Keyes,
Partridge, Ursenbach

ACKNOWLEDGMENT

BIBLIOGRAPHY

(1) "Reaction Kinetics and Thermo-Hydrodynamics of 80/20 Tritonal", Technical Report No. XXIX, March 10, 1954, ERG, Utah University (Confidential).

(2) "Reaction of Aluminum in 75/25 HBX", Technical Report No. XXXIV, May 7, 1954, ERG, Utah University (Confidential).

(3) "Velocity and Wave Shape Studies of AN-Al Mixtures", Technical Report No. XXXV, June 7, 1954, ERG, Utah University (Confidential).

(4) This correlation was first presented by M. A. Cook and L. B. Seely, DuPont shaped charge studies during World War II.

(5) "'Pin Oscillograph' for Measurement of Detonation Velocity", Technical Report No. XXXIII, May 4, 1954, ERG, Utah University.

(6) "Construction of Rotating Mirror 'Streak' Cameras and Synchronizers", Technical Report No. XII, April 30, 1953, ERG, Utah University (Confidential).

(7) "Detonation Velocities of Ideal Explosives with Inert Additives", Technical Report No. XVIII, August 15, 1953, ERG, Utah University (Confidential).

(8) "Recent Developments in Theory of Detonation", Technical Report No. XXV, November 23, 1954, ERG, Utah University (Confidential).

(9) "Calculation of Products of Detonation Using IBM Machines", Technical Report No. XXI, October 16, 1953, ERG, Utah University.

(10) M. A. Cook, J. Chem. Phys. 15, 518 (1947).

(11) M. A. Cook, "Detonation Wave Fronts in Ideal and Non-Ideal Explosives", This Symposium.

(12) H. Eyring, R. E. Powell, G. H. Duffey, R. B. Parlin, Chem. Rev. 45, 1 (1949).

Cook, Filler, Keyes
Partridge, Ursenbach

Table I: Thermo-Hydrodynamic Properties of Aluminized Explosives

	80/20 Tritonal			45/30/25 RDX-TNT-Al			AN-Al Mixtures (log F = 3)					
log F	2.5	3.5	6.0	3.0	4.0	6.0	%Al=>	2	10	15	20	30
n (moles/kg)	25.3	21.2	12.8	23.1	19.5	14.9	43.7	42.7	36.6	33.2	31.3	28.8
T_2 (°K)	3630	4100	5410	3900	4400	5700	3780	2180	2580	4400	4600	4360
D^* (m/sec)	4054	4930	7025	4470	5735	7635	4380	4760	5550	5810	5760	5380
ρ_1 (g/cc)	1.105	1.416	1.785	0.99	1.51	1.82	1.07	1.07	1.06	1.05	1.05	1.05
v_2 (cc/g)	0.641	0.528	0.435	0.712	0.518	0.432	0.727	0.727	0.727	0.727	0.727	0.727
α (cc/g)	0.497	0.446	0.405	0.560	0.442	0.396	0.582	0.582	0.582	0.582	0.582	0.582
Q (kcal/kg)	880	1100	1750	845	1065	1630	355	480	950	1305	1355	1165
Al_2O (mol/kg)	2.79	2.29	0.28	4.461	3.361	1.553	--	0.0	--	0.023	0.875	3.248
Al_2O_3 (mol/kg)	0.91	1.41	3.42	0.174	1.274	3.082	--	0.37	1.855	2.755	2.835	2.312
$P_2^* \times 10^{-3}$ atm	52	85	196	56	107	222	44	53	74	82	81	71

Cook, Filler, Keyes,
Partridge, Ursenbech

Table II: Influence of Al Particle Size in AN-Al Mixtures in
9.94 (d) x 61 (L) cm Charges

Al Particle Size*	$\bar{\rho}_1$ (g/cc)	$\bar{D}(obs)$ (m/sec)	Al Particle Size*	$\bar{\rho}_1$ (g/cc)	$\bar{D}(obs)$ (m/sec)
6 Percent Al			**10 Percent Al**		
-100 + 150	1.13	Failed	- 65 + 100	1.15	Failed
-150 + 200	1.13	Low	-100 + 200	1.12	3085
-200 + 325	1.14	2495	-200 + 325	1.15	3090
-325	1.20	3050	-325	1.20	3225
12 Percent Al			**AN Particle Size**		
- 65 + 100	1.15	Failed	+ 48	13.3	Percent
-100 + 150	1.14	3170	- 48 + 65	60.2	Percent
-150 + 200	1.16	2865	- 65 + 100	22.5	Percent
-200 + 325	1.18	2380	-100 + 150	4.0	Percent
-325	1.20	2900			

*Standard Tyler Mesh

Table III: Critical Diameter Data for AN-Al Mixtures

Percent Al	Particle Size* Al	Critical Diameter d_c (cm)
0	-325	$12.7 < d_c < 15.0$
2	-325	5.0
4	-325	2.5
6	-325	2.5
8	-325	< 2.5
10	-325	2.5
15	-325	2.5
20	-325	$2.5 < d < 5.0$
30	-325	5.0
40	-325	> 7.5
10	- 48 + 325	5.0
12	- 48 + 325	$5 < d_c < 7.5$
15	- 48 + 325	5.0
6	-150 + 200	10.0
10	-100 + 200	10.0
15	- 65 + 100	10.0

*AN approximately the same throughout—see Table II

Confidential

Table IV: Variations of Velocity with Density in AN-Al and AN-DNT Mixtures

90/10 AN-Al (10 x 60 cm)				90/10 AN-DNT (1) (10 x 60 cm)			
AN Sample	$\bar{\rho}_1$ (g/cc)	Charge	D (m/sec)	AN Sample	$\bar{\rho}_1$ (g/cc)	Charge	D (m/sec)
1*	1.06	LP**	3260	1	0.88	LP	3310
1	1.09	p	3390	1	1.00	LP	3460
1	1.19	p	3550	1	1.05	p	3560
1	1.26	p	3350	1	1.17	p	3330
2	0.96	LP	3265	1	1.27	p	3120
2	1.12	p	3485	7	1.08	p	3315
2	1.17	p	3290	7	1.04	pc	3340
2	1.25	p	2530	7	1.17	p	3210
3	1.07	p	3520	7	1.03	pc	3735
3	0.96	pc	3490	7	1.27	p	2905
4	1.18	p	3405	7	1.07	pc	3700
4	1.00	pc	3715				
5	1.28	p	Failed				
5	0.95	pc	3675				
6	1.12	LP	2595				
6	1.11	LP	2525				

*Screen Analysis of samples 1, 6, 7 were as follows:

AN Particle Size Data

Mesh	(1)	(6)	(7)
– 10 + 20	—	5.1	—
– 20 + 35	—	70.9	—
– 35 + 48	—	20.2	6.0
– 48 + 65	48.5	2.9	48.4
– 65 + 100	28.5	0.9	36.9
–100 + 150	10.1	—	4.3
–150 + 200	4.8	—	2.0
–200	8.1	—	2.4

Samples 2, 3, 4, and 5 were the same as sample 1 but had aged to 27 days. Aging of AN causes definite changes, the most significant of which is the packing quality.

**LP = loose packed, p = pressed, pc = pressed and crushed to a loose powder which was then loose-packed. This gave a loose-packed product of the same particle size as in the corresponding pressed charges.

Confidential

Cook, Filler, Keyes,
Partridge, Ursenbach

Table V: Observed Variations of R_1/d with Composition and d in AN-Al Explosives

A. -325 Mesh Al, Fine AN*

Percent Al	d=2.5	5.0	7.5	10.0	12.5	15.0	17.5	20.0	25.0	40.0	46.0
0					Failed		1.16	1.05	0.96	0.78	1.03
2	Failed	Failed		1.26							
4	0.92	1.33	1.31	1.27	1.32						
6	1.35	1.25	1.55	1.35	1.38						
8		1.37	1.39	1.39	1.43	1.21	1.31	1.21	1.35		
10		1.58	1.56	1.49	1.39						
15	1.07	1.54									
20	Failed	1.39	1.53								
30		Failed	1.59								

B. Fine AN, + 325 Mesh Al (by removing -325 mesh material from standard)**

Percent Al	d=2.5	7.5	10.0	12.5	15.0	17.5	20.0	25.0
10	Failed	1.61	1.48	1.50		1.53	1.37	1.67
12	Failed			1.36	1.29	1.36	(1.26)	1.55
15	Failed	1.70		1.33	1.63	1.52	1.42	1.45

C. 150 to 200 Mesh Al

Percent Al	10.0
6	0.99
10	1.31
15	1.30

*AN Particle Size

+ 48 mesh	0 - 31 percent
- 48 + 65 mesh	24 - 40 percent
- 65 + 100 mesh	8 - 40 percent
-100 + 150 mesh	4 - 25 percent
-150 mesh	Negligible

**Standard Al Particle Size

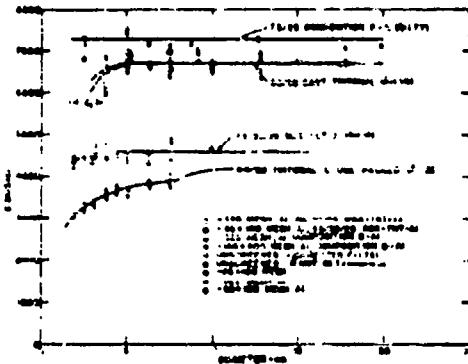|	
+ 65 mesh	14.9 percent
- 65 + 100 mesh	15.1 percent
-100 + 200 mesh	20.9 percent
-200 + 325 mesh	12.7 percent
-325 mesh	36.4 percent

Fig. 1- Velocity-Diameter Curves
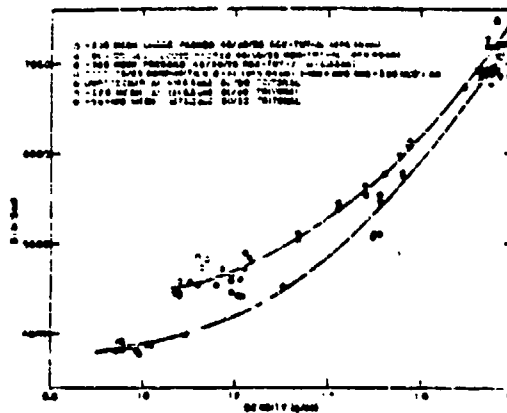for 80/20 Tritonal and 45/30/25
RDX-TNT-Al.

Fig. 2 - Ideal Velocity-Density
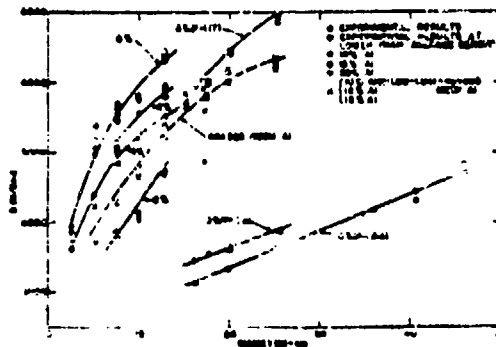Curves for 80/20 TNT-Al and
45/30/25 RDX-TNT-Al.

Fig. 3 - Velocity-Diameter Curves
for AN-Al Mixtures (-35 + 150 mesh
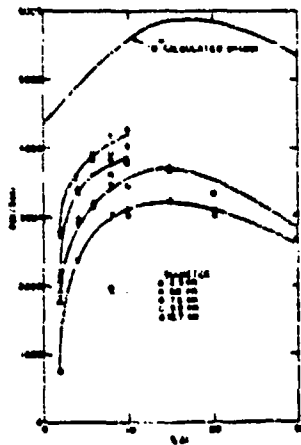AN, Al was -325 mesh except as indi-
cated, $\bar{\rho}_1$ = 1.0-1.05).

Cook, Filler, Keyes
Partridge, Ursenbach

Fig. 4 — Velocity vs.
Percent (-225 mesh)
Aluminum ($\delta_1 = 1.0$ 1.05)
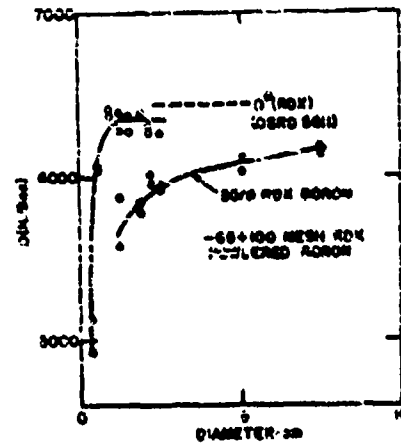
Fig. 5 — Velocity vs. Diameter
Measurements in RDX and 95/5
RDX-Boron Mixtures (Corrected
to $\delta_1 = 1.1$)
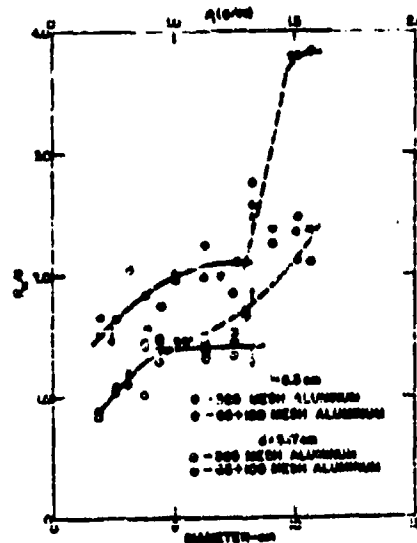
Fig. 6 — R_c/d vs. Diameter Curves
for Aluminized Explosives

CONDITIONS BEHIND THE REACTION ZONE OF CONFINED
COLUMNS OF EXPLOSIVE —
DEDUCTIONS DERIVED FROM PLATE DENT EXPERIMENTS

W. M. Slie, R. H. Stresau
U.S. Naval Ordnance Laboratory
Silver Spring, Maryland

Introduction

It is convenient to consider detonation in one dimensional terms.
Much of our insight regarding the processes involved is derived from
such considerations. In physical terms, one dimensional consideration
of detonation is equivalent to the assumption of an infinite plane
wave, or perfect confinement of a finite column. Of course, neither
of these conditions is realizable in that rarefaction waves close in
radially as well as from the rear. In columns larger than an inch or
so in diameter, for most explosives, the effect of the rarefaction
waves upon the reaction zone, and hence upon the stability and
velocity of detonation, are negligible. Even quite small columns of
most high performance explosive compounds, when highly confined in
metals, show relatively little diameter effect. In any size charge,
however, the dimensions and conditions of the head of rapidly moving,
high pressure gases which follow the detonation are directly determined
by the nature of these rarefactions. The detonation head is a
manifestation of flow conditions behind the detonation front. The
pressure, density, and temperature drop are determined by these flow
conditions, which are in turn determined by the geometry of the case
in which the charge is confined. The geometry of the case, of course,
is continuously modified by the forces of the detonation.

A rigorous treatment of flow conditions in and behind the
reaction zone is beyond the scope of available methods, and would
require information which is not available. Treatments based upon
reasonable assumptions, sometimes quite obvious approximations, have
provided bases for qualitative understanding and sometimes lead to
semi-empirical equations which check well with experiment.

Important contributions to the understanding of the effect of
radial losses upon the stability of detonation were made by Jones[2]
and by Eyring and his co-workers[1]. For these purposes, the flow

CONFIDENTIAL

need be considered only to the extent that it affects conditions within the reaction zone. The curved front theory of Eyring and his co-workers[1] is quite useful for this purpose. The relation between the curvature of the front and conditions several charge diameters back would be difficult to establish and more difficult to work with. The flow behind the reaction zone has been analyzed for several sets of special conditions including those for the edge of a semi-infinite charge[3] and a thin cased cylinder[4].

It has been noted that a very small charge of explosive heavily confined in metal, behaves quite similarly, in some respects, to a much larger bare charge. This fact has led to the development of a small scale technique for the measurement of detonation velocity[5]. Associated with the proven usefulness of larger scale plate dent tests[6] it inspired the hope that a useful means of evaluating explosives of which only small quantities are available might lie in a dent test in which the dents are produced by small, highly confined, charges.

The results obtained in the first small scale dent experiments were systematically related to properties of the explosives used, but do not correlate well with the larger scale results of Smith and Eyster[7]. The obvious reason for this difference in results was the large difference in the confinement used in the two types of test. Since explosives were included which exhibited little diameter effect, it was reasoned that the effect of confinement upon dent test results must be a manifestation of its effect upon the conditions behind the reaction zone. The explosive columns used in most of the small scale experiments were confined in metal cylinders so thick that further increase had negligible effect upon the results. The thin cased charge analyses quite clearly do not apply to these experiments but the outer boundaries of the case need not be considered.

A useable expression has been derived which relates the depth of dent to the properties of the explosive and confining medium. An important assumption in this derivation is that the length of the "head" of high pressure product gases following the detonation is determined by the relation between the equations of state of the explosive and the confining medium. The present paper includes a discussion of the application and limitations of the use of this expression together with illustrative data.

Experimental Technique and Arrangement

As stated above, the dent produced by small, highly confined, columns of explosives was first considered as an economical means of evaluating experimental explosives. The small amount of equipment needed was a very attractive feature. To explore the possibilities of such a test a series of trials was made with the general arrangement shown in Figure 1.

131   CONFIDENTIAL

The explosives were loaded into heavy walled brass tubes made by drilling and reaming bar stock. The tubes were counterbored at one end for the insertion of an electric initiator. Most of the tubes were two inches long with about a half inch deep counterbore, leaving about one and a half inches for the explosive column. Several sizes of tubes were used including 0"10, 0"15, 0"20 and 0"25 inside diameters. The ratio of the outside diameter of the tubes to the inside diameter was never less than 6.67. It is believed that this ratio was large enough for adequate confinement in each case, and that any further increase would have had a negligible effect. The blocks in which the dents were made were two inch long pieces cut from one by two inch cold finished, SAE 1020, steel bars. The dent was made in one of the broad faces which was cold finished.

The explosive was loaded by increments at 2,000 psi, 8,000 psi, or 32,000 psi. Increments were limited in length to not more than the diameter of the hole in order to reduce the variations in density due to wall friction which occur when longer increments are used. Densities were determined from the loading pressures using the relations given by Hampton[8]. In some cases, these values were verified by measurements of the volume and mass of explosive columns. Electric initiators with bridge wires attached by the spray-metal process[19] loaded with flash charges of fifty milligrams of milled lead azide at 4,000 psi were used.

The depths of dents were measured to the deepest part of the dent from the flat surface of the block at a distance far enough from the dent to have been undisturbed by the explosion. An Ames dial indicator pedestal height gage was used. The deepest point can easily be located by moving the block with respect to the feeler of the gage until a maximum deflection is observed. The depth was measured with respect to at least two opposite points on the surface to check the flatness. If the two readings agreed within one thousandth of an inch they were averaged. Greater disagreement indicated dirt under the block, since the flatness had been checked before the test.

The results of the exploratory tests indicated that the effect of confinement upon dent test results might be much greater than upon detonation velocity measurements. For this reason, a number of trials were made using a variety of confining media and tubes of varying thickness.

The detonation velocities of the explosives used in the first group of experiments were estimated from the densities, which in turn were estimated from the pressures at which they were loaded. In the more recent experiments both the density and the detonation velocity were measured for each trial. The densities were computed from measurements of the dimensions of the hole into which the explosive was loaded and weights of explosives determined by weighing the containers before and after loading. The detonation

CONFIDENTIAL

velocities were determined by measuring the time required for the
detonation to traverse the last inch of the column. The velocity
measurement was essentially that described by Kempton[5]. The timer
used was the vacuum thermocouple timer described by Stresau and
Goode[9]. In order to measure the detonation velocity, the container,
as well as the explosive column, was made in sections to facilitate
the insertion of an ionization probe one inch from the end. An inch
long column, as nearly identical to the final inch as possible, both
as to loading and confinement, preceded the section over which the
velocity was measured. This latter section was for the purpose of
insuring that the detonation had stabilized before the velocity was
measured.

Results and Discussion

The dents obtained, Figure 2, were more or less cylindrical
with nearly flat bottoms. The charges used were small enough so that
the only measurable deformation of the plate other than the dent was
a slight swelling, about 0.002, which was radially symmetrical to the
dent. In Figure 3 the depths of dents obtained with four high
explosives and four column diameters are plotted versus the
detonation velocities of the explosives loaded at the same densities.
The velocities used in this plot were determined from the loading
densities using detonation velocity-density data from M.D. Hurwitz[10].
Note the linear relationship of depth of dent to detonation velocity.
The convergence of the lines at a point is probably not significant.
The charge was detonated with a few increments of lead azide between
the initiator and the main charge, Figure 1. This detonator charge
could cause considerable difficulty if it had to be considered in the
interpretation of results. However, if the assumption can be made
that the dent is caused entirely by the charge material, a fairly
simple relationship between the depth of dent and the properties of
the explosive may be derived. It was therefore necessary to
determine the variation of depth of dent with length of explosive
column.

A study of the effect of charge dimensions on the depth of dent
was undertaken. Charges of lead azide and tetryl in which the
fractional column lengths of the two materials were varied were
detonated on the surface of metal plates and a measure of the depth
of dent was made. The explosives were loaded in columns of total
length 0.5, 1.0, and 1.5 at 8,000 psi in heavy walled containers.

The results of these experiments are plotted in Figure 4. Note
that both the total column length (Y) and the length of the tetryl
column (y) affect the depth of dent when these quantities are small,
but when the total column length exceeds about an inch and the
length of the tetryl column is over approximately five diameters,
the depth of dent becomes independent of both of these dimensions.
A similar experiment was performed in which the depth of dent was
determined as a function of total column length for lead azide,

Figure 5. In this experiment a standard length of tube was used so
that the air gap between the initiator and the column decreased as
the column length increased. The slope of the curve seems to
indicate that the effect of this change in gap between the initiator
and explosive column is negligible. The depth of dent becomes
independent of the length of the column when the column length exceeds
about a half inch. The larger relative dispersions with lead azide
may be attributed at least in part to the residue of lead which had
to be removed from the dent before making measurements.

A rather interesting feature of the results of these
experiments is the nearly linear relationship between the depth of
dent and the detonation velocity, Figure 3. These results may be
contrasted with those obtained in larger scale experiments, Figure 6,
in which it was found that the depth of dent varied linearly with
$\rho_o D^2$, where D is the detonation velocity and ρ_o is the density at
which the explosive was loaded. This apparent contradiction may be
explained by the fact that the larger charges were bare while the
smaller charges discussed herein were highly confined in metal. It
is believed that the following qualitative discussion may aid in
understanding what was experimentally observed. Consideration of
dents in metals has usually been in connection with measuring their
hardness. A generality which may be inferred from hardness theory
and data is that the work done in producing a dent is proportional
to the volume of the dent.

The size and condition of the "head" of rapidly moving, high
pressure gases which follows a detonation is directly determined by
the nature of the rarefaction waves which follow from the rear and
close in radially. In columns whose lengths are large enough
compared with their diameters, the head reaches a stable condition
which is determined by the boundary conditions at the cylindrical
surface of the column. Both the size of the head and the length of
the column required for it to stabilize itself depend upon what is
considered to be part of the head. Gamow and Finkelstein[11], define
the head as all of the forward moving gases, but for the purpose of
the present discussion, it will be arbitrarily defined as the material
which contributes measurably to the deformation of the steel block.
By definition metal can be permanently deformed only by stresses in
excess of its elastic limit. The pressure which a moving fluid can
exert upon a surface is the sum of the static pressure (P) and the
kinetic pressure $\frac{\rho u^2}{2}$, where ρ is the density and u is the particle
velocity normal to the surface. This sum

$$1) \qquad \frac{u^2}{2} + P = H$$

will be known herein as the "total pressure". It will be assumed
that the head includes that gas for which the total pressure exceeds
the elastic limit of the metal.

In considering the effect of diameter and confinement upon the detonation velocity of explosives, Jones[12] develops his argument on the basis that the expansion of the case allows expansion of the explosives during the reaction time, an approach characterized by Eyring[1] as the "nozzle theory". In considering conditions behind the reaction zone, the nozzle concept becomes even more useful. At the end of the reaction zone, according to the Chapman-Jouguet theory, the sum of the sound velocity and the particle velocity is equal to the detonation velocity. In terms of ordinates moving at the detonation velocity this means that the particle velocity is equal to the sound velocity which is the throat condition of an ideal de Laval nozzle.

Courant and Friedrichs describe a "hydraulic" treatment, similar to that of Reynolds, whereby very good approximations of flow conditions in a de Laval nozzle may be obtained. Introducing a set of surfaces of revolution, perpendicular to the wall, it is assumed flow is orthogonal to them and that all relevant quantities are constant on them. Further assuming that the adiabatic expansion of the gas follows the law that PV^γ is constant, that the flow is irrotational, and Bernoulli's law, a set of equations is derived relating the particle velocity, the cross section area, the sound velocity, the density, and the pressure by various functions of gamma.

The shape of the nozzle formed by the expanding case is determined by the interaction of the explosive forces and the resistance of the metal to deformation. The assumption of a simple conical nozzle, while satisfactory for consideration of reaction zone phenomena becomes increasingly unrealistic as the length under consideration increases because it implies an unlimited source of energy. An assumption which is not unreasonable is that at all points on the surface of the nozzle the pressure is equal to the product of the shock velocity, the particle velocity, and the density of the metal. This follows from a not too critical application of the law of conservation of momentum. If this relationship is combined with the nozzle equations, a completely unmanageable set of expressions can be derived. If, however, simple integers, such as two or three, are substituted for gamma, it is possible to obtain numerical solutions for the various flow quantities by a process of iteration. The system scales in terms of the dimensionless quantity $L\rho_e D_e / r\rho_c D_c$, where L is the distance behind the front, ρ_e is the density of the explosive, D_e is the detonation velocity, r is the radius of the explosive charge, ρ_c is the density of the confining medium, and D_c is the velocity of a shock in the confining medium.

If it is assumed: that the detonation "head" scales in terms of the dimensionless quantity mentioned above; that the volume of a dent in steel is proportional to the energy expended in producing it, that the energy delivered to the plate is proportional to that in the "head"; and that, for a constant diameter explosive charge, the volume of the dent produced is proportional to its depth, the following

CONFIDENTIAL

expression may be derived by some rather simple but space consuming
algebra (20):

2) $\quad\quad\quad\quad d/r = k \, \rho_c D_c \, (D_e \cdot S/\rho_e D_e)$

where S is a constant related to the strength of the steel. S and k
can be determined using two experimental points obtained with
explosives for which the relationship between density and detonation
velocity is known. In Figure 7, the agreement between the
experimental data and the curves plotted from the equation is quite
remarkable.

It will be noted that equation 2) predicts that the depth of
dent should be proportional to the shock impedance, the product of
the density and the shock velocity, of the case. A series of
experiments was undertaken to test this prediction. These
experiments differed from the previous ones mainly in that the
confining medium was varied. The results of these experiments are
shown in Tables I and II. The compositions of the confining media
are given in Table III. It is seen from Table I, which shows the
effect of case confinement for small charges of PETN, that the
detonation velocity of the PETN does not change as a function of the
confining media. However, the output of the charge, as measured by
a dent test, does change with the confining case and is directly
related to the characteristic shock impedance of the confining case.
Note the agreement between the shock velocities measured using
entirely different methods. This is an indication that the time for
the reaction of the PETN to be completed is so short that the
conditions in the reaction zone are not changed by confinement, but,
since the measured output of the PETN charge is changed, the flow
conditions in the detonation head must have changed.

The process which takes place in TNT when confined in various
media is not so simple, as shown by an inspection of Table II, and
in a more specific case, that is, for TNT confined in steel, as
shown in Figure 8. For this explosive there is both a velocity
change and an output change due to confinement. This is seen by
comparing the measured velocity and the large scale velocity for the
same density. The detonation velocity called large scale velocity
in this report is that obtained from experimental rate-loading
density data, and for TNT the difference between the measured
velocity and this value decreases as the loading density is
increased. This indicates that the reaction zone length of the
explosive is an inverse function of density.

A comparison of the reaction zone lengths for PETN and TNT
may be obtained using relationships derived by Eyring et al [14].

$$\tan \phi = \frac{\rho}{\rho_c}\sqrt{\frac{D}{D_c} - 1}$$

$$\frac{D}{D_i} = 1 - .88 \frac{a}{R}\sin\phi$$

assuming $\cos\phi \approx 1$

3) $\qquad \frac{D}{D_i} = 1 - .88 \frac{a}{R} \frac{\rho}{\rho_c}\sqrt{\frac{D^2}{D_c^2} - 1}$

where D = detonation velocity (measured)
$\qquad$ D_i = ideal detonation velocity (large scale)
$\qquad$ a = reaction zone length
$\qquad$ R = radius of the charge
$\qquad$ ρ = density of explosive charge
$\qquad$ ρ_c = density of case
$\qquad$ D_c = shock velocity

substituting values from Table I for PETN confined in steel
(ρ = 1.35) a = .12 mm

substituting values from Table II for TNT (ρ = 1.36) a = 2.4 mm

substituting values from Table II for TNT (ρ = 1.58) a = .106 mm

The values obtained for the length of the reaction zone agree in a
quantitative way with the upper limit values given by Eersberg(21),
if we assume that the reaction zone length of PETN is shorter than
that of TNT from the effect of confinement on each explosive, and
from the comparative sensitivity of each explosive. Thus one sees
that the reaction zone lengths for the two explosives, TNT and PETN
differ appreciably for similar conditions of confinement and loading.

The results obtained with aluminum and magnesium are an odd
combination of a vindication of these equations and an illustration
of their limitations. It is clear from a glance at equation 3) that
the predicted effectiveness of a confining medium increases so
sharply as its shock velocity approaches the detonation velocity of
the explosive that its density assumes a secondary importance. It
will be noted that the detonation velocities of TNT which was loaded
in aluminum and magnesium, which have high shock velocities but low
densities, are higher than those confined in babbitt. As predicted
by equation 3), which applies to the reaction zone, aluminum is a
better confining medium than babbitt so far as detonation velocity
is concerned, but as predicted by equation 2) which was derived
considering the whole detonation beam, babbitt is a better confining

medium than aluminum as indicated by the dent test. The difficulty
arises when an attempt is made to use equation 3) quantitatively.
The meaning of the imaginary quantity resulting from the substitution
of a shock velocity higher than the detonation velocity is somewhat
difficult to grasp.

All of the confining tubes used in the experiments described
above were so thick that it was assumed that further increase in
thickness would have negligible effect. A series of experiments was
run with tubes of varying thicknesses. The results of these
experiments are given in Tables IV and V. The one inch outside
diameter tubes used in the previously mentioned experiments are
obviously large enough to justify this assumption. Results obtained
with PETN are given in Table IV. Neither the material nor the
thickness of the confining tube has an effect on the detonation
velocity of PETN which is large enough to be detected with the
instrumentation used. The dent produced, however, varies systemati-
cally with the outside diameter for each confining medium.

Since the results of the experiments with the denser confining
media were more nearly as expected, these experiments will be
considered first. In terms of the interpretation of dent test data
on which this paper has been based, the effect of the outside
diameter of the tube upon the dent should be felt when this diameter
is small enough that the rarefaction wave which is the reflection
of the shock wave from the surface reaches the bore of the tube
within the length of the detonation head. If it is assumed that
shock and rarefaction waves of all amplitudes have a constant
velocity, the distance, "L", from the detonation front to the point
where the rarefaction wave intersects the bore can be obtained from
the simple trigonometric relationships:

4) $\sin B = D_c/D_e$ 5) $L = 2t\cot B$

where B is the angle between the axis and the shock front in the
metal and "t" is the thickness of the tube. If we apply these
equations to the data for PETN confined in steel, the length of
head determined is in the neighborhood of three millimeters. The
larger variation of shock velocity with amplitude in the other
materials makes the wave front geometry too complicated to express
in these simple terms, but an order of magnitude correlation might
be expected. Brass, whose shock velocity and density are close to
those of steel, is quite similar in its behavior as a confining
medium both with thick and thin walls. The outside diameter at which
the effect of the surface rarefaction is noticeable should be
smaller for babbitt both because as a poorer confining medium it
would support a shorter detonation head and because of its lower
shock velocity, the ratio of "L" to "t" in equations 4) and 5)
is larger. This expectation is realized, Table IV.

CONFIDENTIAL

Equations 4) and 5) cannot be applied to aluminum and magnesium because their shock velocities exceed the detonation velocity of the explosive. An interesting feature of the magnesium and aluminum data is the sharp increase in depth of dent with decreasing diameter at about 0.45 inch outside diameter. Observation of the shapes of the dents produced left no doubt that this increase was associated with a substantial contribution by the case to the denting. Apparently these materials, due to their good impedance match to the explosive, acquire enough forward momentum to contribute appreciably. The rather sharp break at 0.45 inch diameter may be associated with the distribution of this momentum over so large an area that the pressure exerted on the steel was reduced below the rather definite yield point of this material.

The results obtained with TNT in tubes of varying diameter, Table V, are quite similar to those obtained with PETN, except that both the material and thickness of confinement affect the detonation velocity. The decrease of detonation velocity with the outside diameter of the steel tubes is about what might have been anticipated. The apparent increase of detonation velocity with decreasing outside diameter of the babbitt tubes was quite unexpected and has not yet been explained. The possibility of measurement aberrations is being investigated.

The "hydraulic" treatment of the de Laval nozzle is based on the assumption that radial pressure gradients are negligible. For nozzles with small expansion angles this assumption is quite realistic. As expansion angles increase, however, so do radial pressure gradients. The expansion angles of the nozzles formed by the interaction of detonating explosives with the confining media increase as the shock impedance of the media decrease. The resulting increase in radial pressure gradients is quite apparent in the shapes of dents produced by the impingement of the detonation on steel plates. As the shock impedance of the confining medium is decreased, the shape of the dent changes from the nearly flat bottomed configuration of Figure 2 to the nearly conical dents produced by unconfined charges.

A nozzle promotes the conversion of thermodynamic energy to kinetic energy by presenting a surface to the expanding gases at such an angle that a component of the force is in the direction of acceleration. The magnitude of this component is proportional to the product of the pressure and the sine of half the expansion angle. For small angles, the pressure change is small and the acceleration increases with the angle. For larger angles where the radial pressure gradients are appreciable, the pressure at the surface decreases until, at some angle depending upon the thermodynamic characteristics of the gas, it reaches zero. The axial component of force, in such a system, must go through a maximum. In the nozzles formed from confining tubes by detonations, the nozzle angles, varying in accordance with the principles discussed above, also may

CONFIDENTIAL

be expected to go through optimums for acceleration of the gases
as they change with the shock impedance of the tubes. It should be
kept in mind that this acceleration is in the opposite direction to
the detonation velocity so that the optimum acceleration would
correspond with a minimum forward momentum and a minimum dent. In
Table VI the data obtained by Savitt[18] seem to support this
expectation.

The agreement between equation 2) and experimental data shown
in Figure 3 was partly the result of the similarity of the equations
of state of the reaction products of the explosives used in these
experiments. The general usefulness of detonation velocity as a
criterion of explosive performance also stems from this similarity.
For some purposes and with certain explosives the lack of correlation
between detonation velocity performance is probably related to
variations in equation of state. An example of this was a mixture
of RDX with about twenty-three percent of wax and plastic resins.
Fragmentation results with this explosive gave much poorer results
than would be anticipated from the detonation velocity. This
explosive also made smaller dents than were predicted by equation 2).
Further investigation may lead to more accurate predictions of
explosive performance by the use of the small scale dent test combined
with the small scale detonation velocity measurements.

Conclusions

Some conclusions which may be drawn from the foregoing are that:

1. The depth of the dent which is produced by the impingement
of a detonation upon a steel plate is a function of the length of the
detonation head as well as the peak detonation pressure.

2. That the use of the concept of a de Laval nozzle, formed
by the action of the explosive on the confining medium, which travels
with the detonation makes possible the derivation of an expression
relating the depth of dent to the properties of the explosive and
of the confining medium which correlates well with experimental data
for charges confined in thick metal tubes.

3. That the nozzle concept may be applied to thinner tubes.

4. That the nozzle concept also may be applied to long
cylindrical charges of any confinement if a more generalized treatment
of nozzle flow than the "hydraulic" treatment is used.

5. That the dent test, combined with detonation velocity
measurements, can make more reliable predictions of explosive
performance possible where equation of state variations affect the
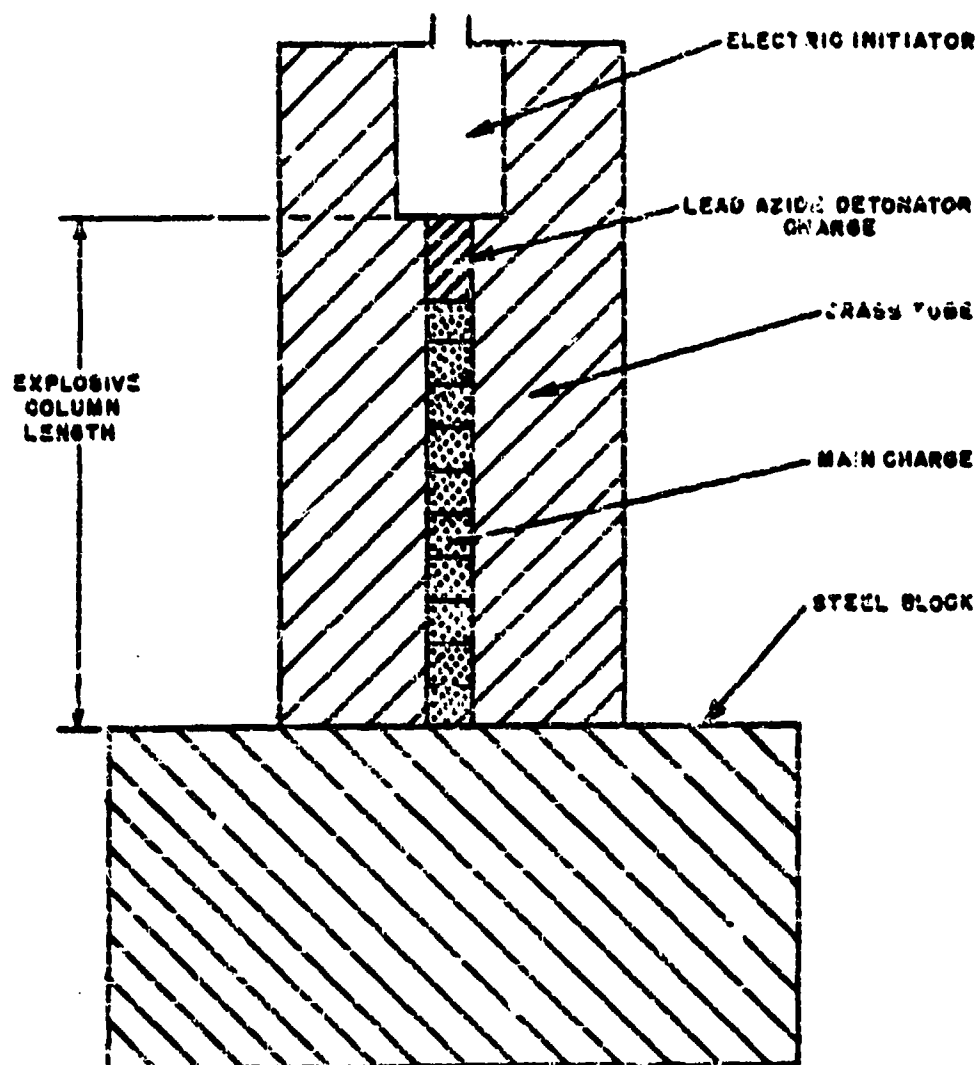reliability of prediction based on detonation velocity alone.

FIG. I
SMALL SCALE DENT TEST
(EXPERIMENTAL ARRANGEMENT)

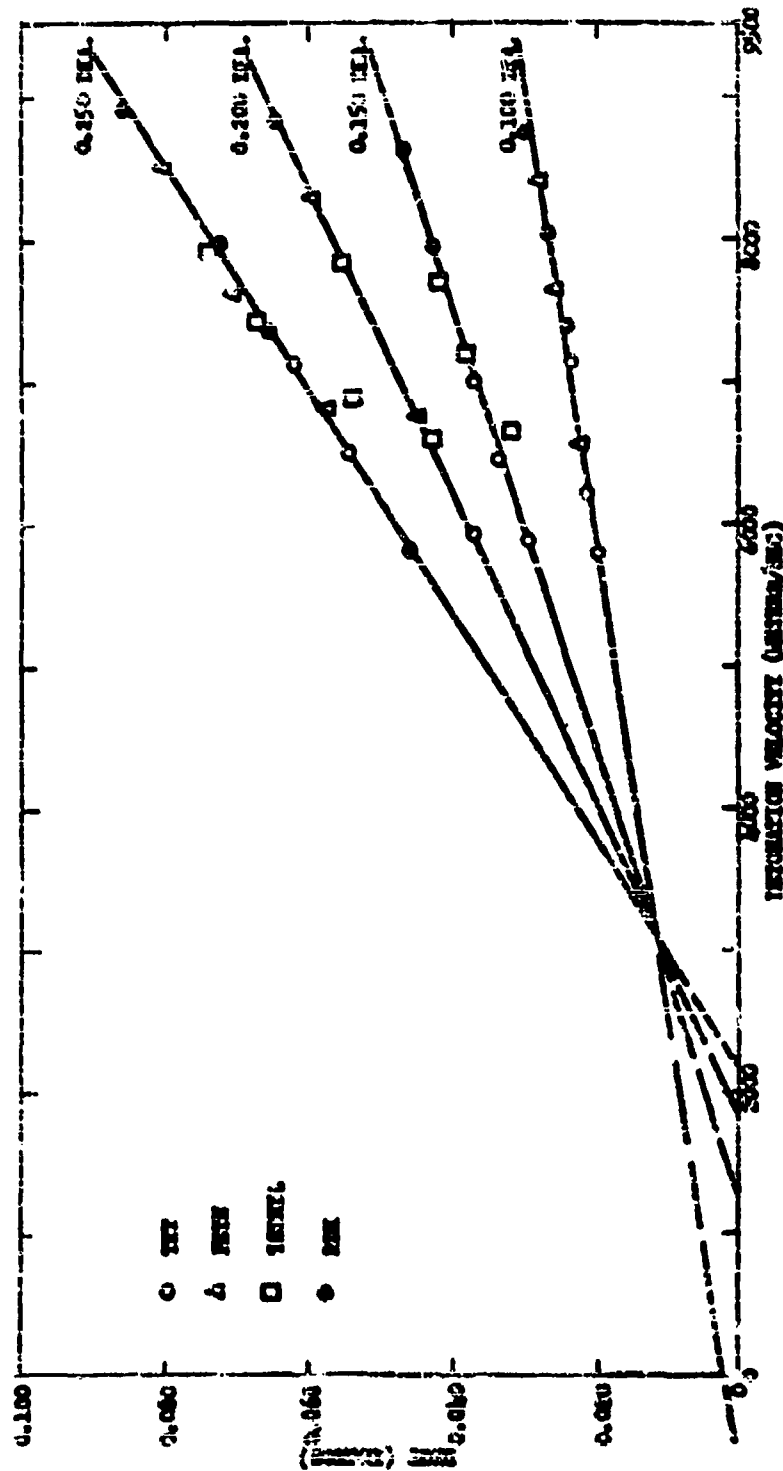FIG. 2

CROSS SECTIONAL CUT OF METAL
BLOCK SHOWING DENT

FIG. 3 INDEX OF END OF STEEL BLOCK vs IMPRESSED VELOCITY
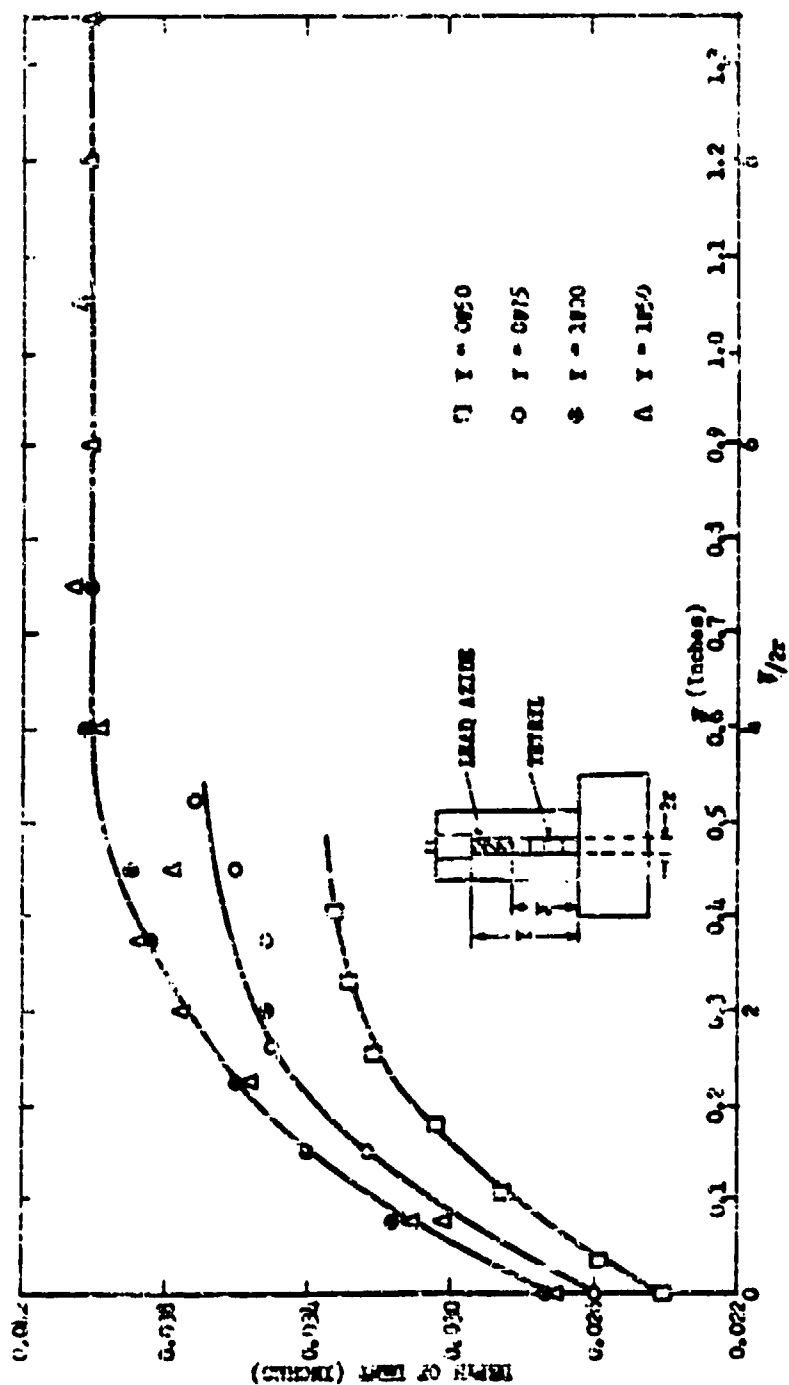
FIG. 4 DEPTH OF DENT IN STEEL BLOCKS vs COLUMN LENGTH OF TETRYL
IN COMPOSITE COLUMN; 0.150 DIAMETER OF LEAD AZIDE AND TETRYL
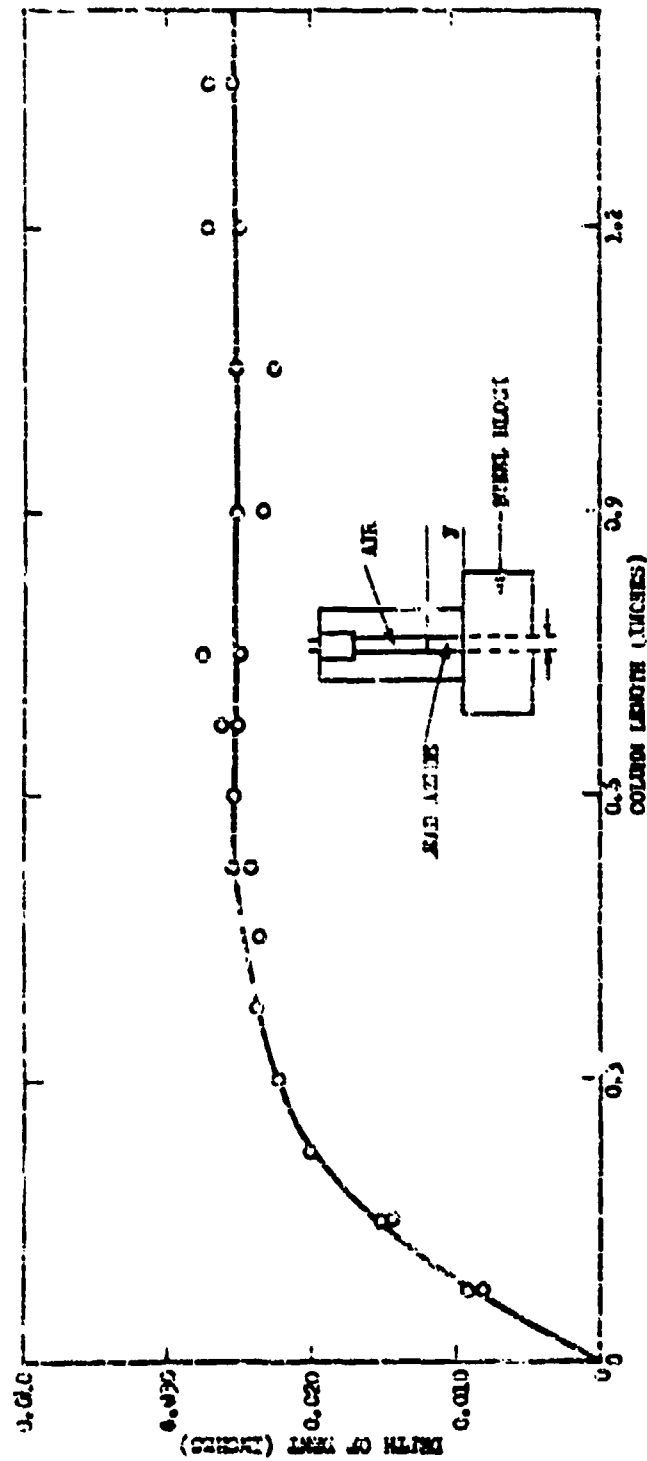
FIG. 5 DEPTH OF DENT vs COLUMN LENGTH LEAD AZIDE OPTSO DIAMETER

CONFIDENTIAL

FOR UNTAMPED CAVITY EXPLOSIVE CHARGES
C = CAST DENSITY OF EXPLOSIVE
D = DETONATION VELOCITY

Dent data in OSRD #5744
Velocity data in OSRD 5611

A = Amatol	50/50
B = Baratol	43/27
C = Comp B	52/48
D = Picratol	52/48
E = Ednatol	52/48
+ = TNT	
P = Pentolite	50/50
T = Tetrytol	75/25
2 = PTX-2	
R = RDX	

$\rho_0 D^2$ (gm/cm sec²)

DEPTH OF DENT (INCHES)
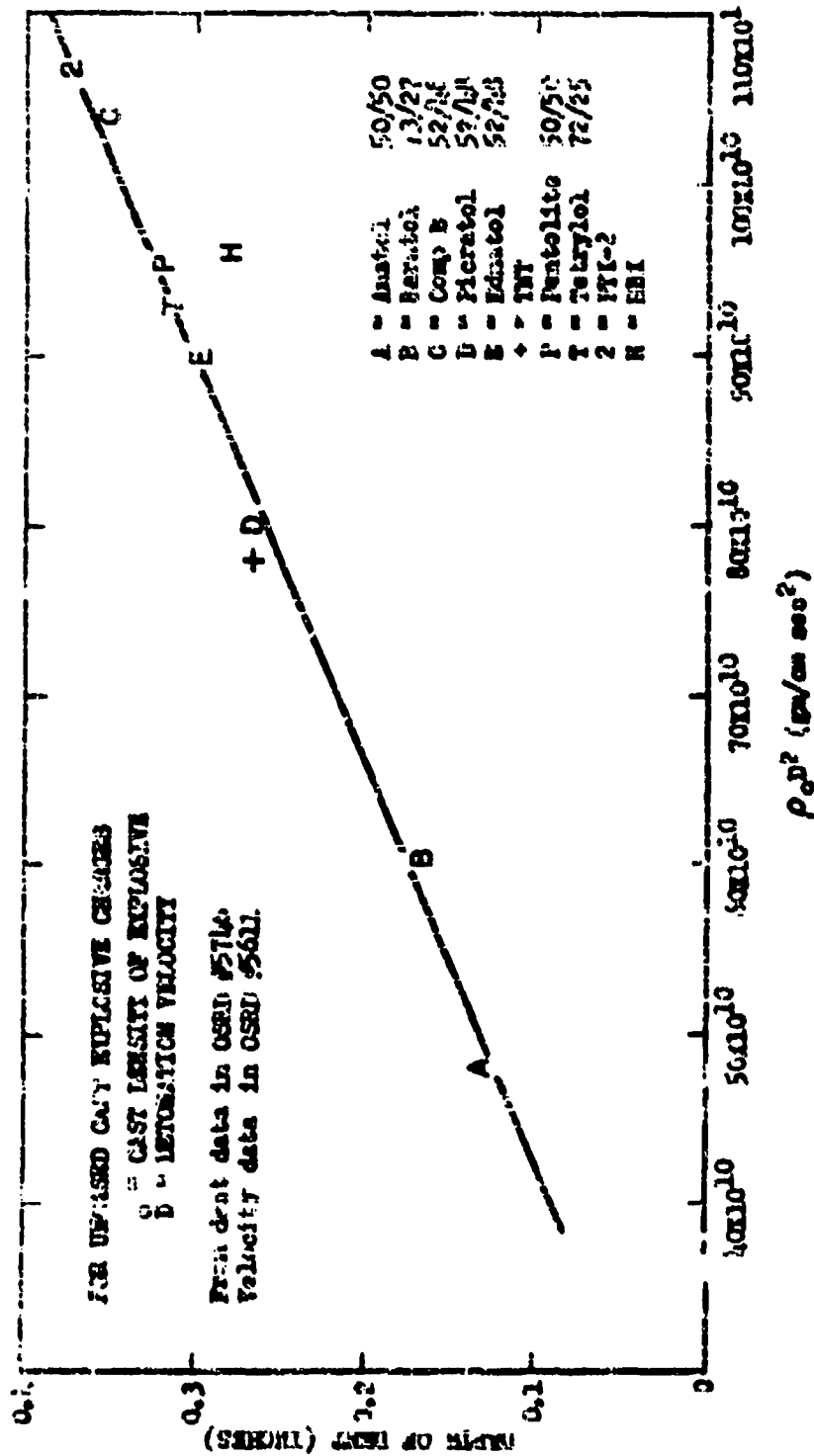
FIG. 6 DEPTH OF PLATE DENT vs $\rho_0 D^2$

CONFIDENTIAL

FIG 7

DEPTH OF DENT DIVIDED BY THE
RADIUS VS DETONATION VELOCITY
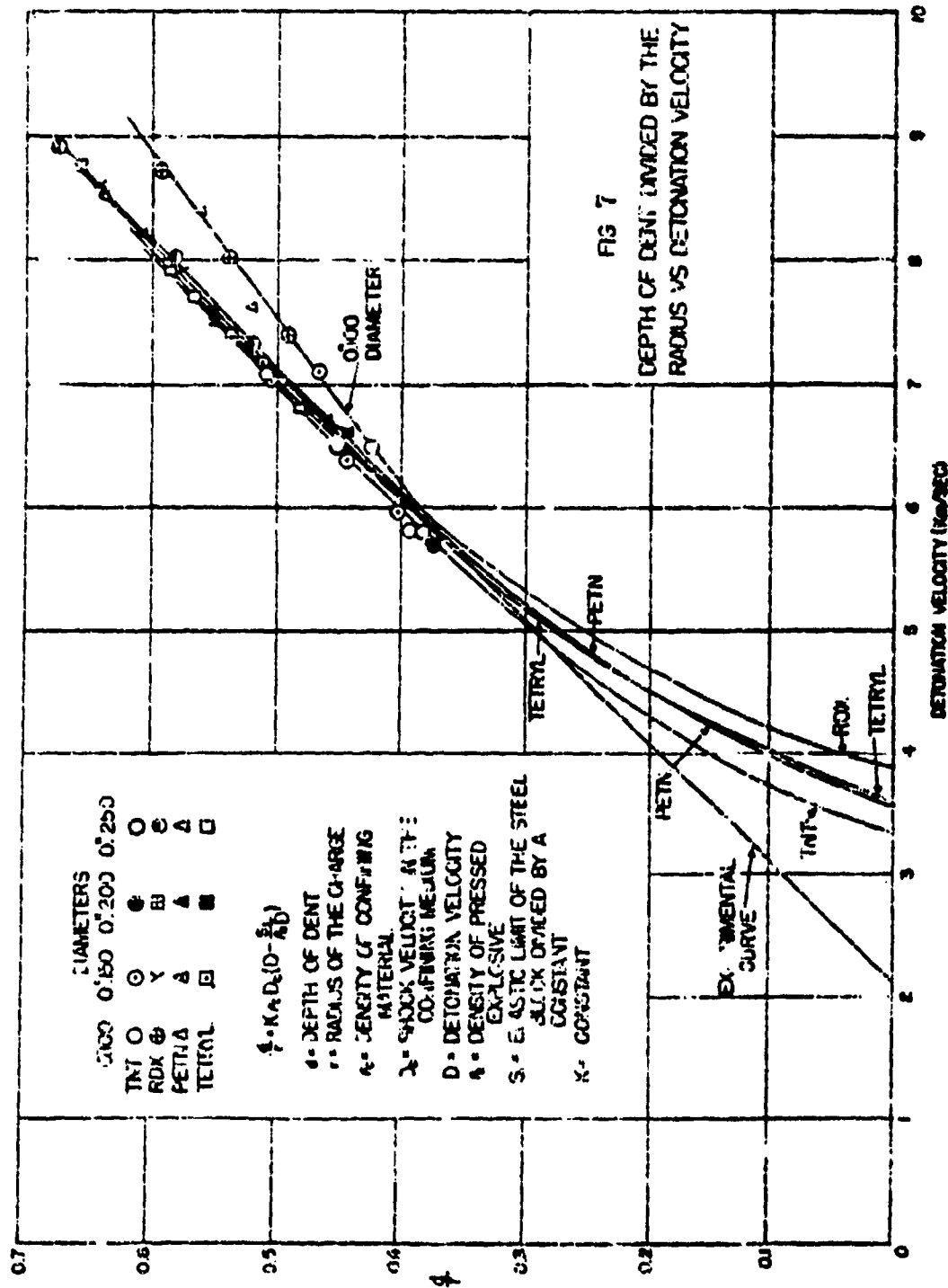
Slie, Stresau

Figure 2
Detonation Velocities of Small Diameter Columns of
TNT Confined in Heavy Steel Tubes

Table I

Effects of Radial Case Confinement for Small Cylindrical Charges of PETN

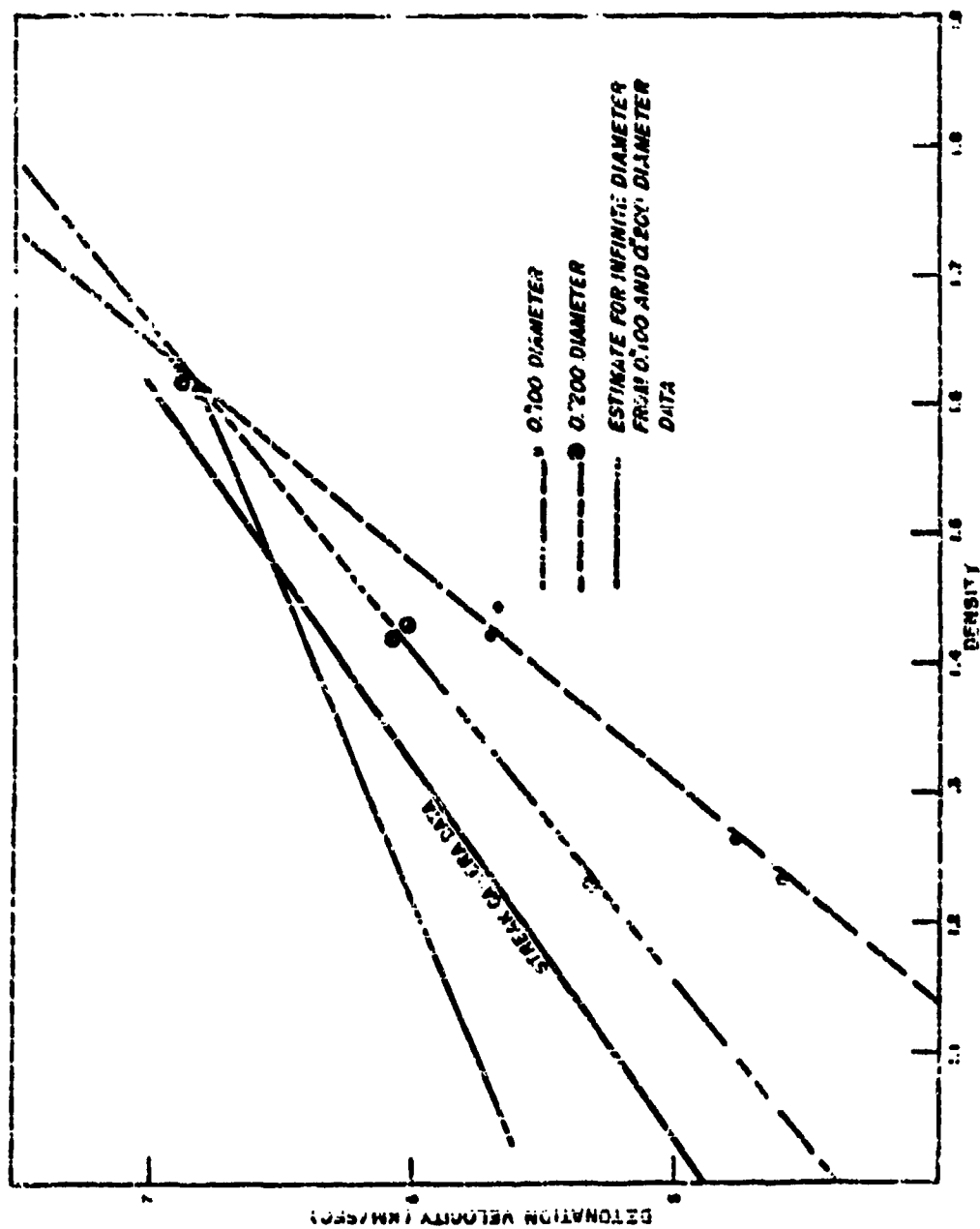| Confining Medium	d	d/r	D_e	D_i	ρ_e	ρ_c	D_c	D_c'
Zinc Alloy Die Cast	24	0.32	6750	6800	1.362	6.60	4050	
	22	0.30	6850	6850	1.368		3850	
Magnesium Die Cast	12	0.17	6750	6950	1.380	1.61	7834	
	12	0.17	6700	6950	1.380		7834	
Brass	35	0.47	6850	6850	1.355	8.50	4519	4350[13]
Regular Brass	36	0.48	6650	6950	1.370	8.50	4615	4291[14]
Bronze	31	0.42	6700	6950	1.376	8.80	4519	*4730[15]
	30	0.40	6600	6850	1.357		5135	
Katos Steel	31	0.41	6050	6400	1.242	7.84	4850	
	35	0.47	6250	6350	1.224		5450	
Regular Steel (1020 Steel)	36	0.48	6500	6500	1.250	7.85	5240	5882[14]
	37	0.50	6400	6800	1.351		5610	5240[16]
Babbitt	27	0.37	6550	6700	1.312	9.73	3274	**3020[16]
	27	0.37	6650	6750	1.322		3217	
Magnesium	13	0.17	6800	6950	1.383	1.76	7834	
Aluminum	17	0.23	6900	6950	1.382	2.71	6886	
	18	0.24	6800	6950	1.385		7150	7103[17]

d-depth of dent (thousandths of an inch); r-radius of explosive column (thousandths of an inch); D_e-detonation velocity (meters/sec) as measured; D_i-detonation velocity (meters/sec) from large scale measurements for density (ρ_e); ρ_e-density at which each specimen was loaded, ρ_c-density of confining medium; D_c-shock velocity in confining medium (meters/sec) calculated from data for each trial using equation 2); D_c'-shock velocity in confining medium measured by others, using various techniques, for shocks produced by explosives

*Copper
**Lead

Table III

Composition of Metals Used for Confinement

Zinc Alloy Die Cast	Aluminum 4.1%; Magnesium 0.04% Zinc remainder
Magnesium Alloy Die Cast	Aluminum 9.0%; Manganese 0.13% Zinc 0.70%; Magnesium remainder
Brass	Copper 62.00%; Zinc 35.00%; Lead 3.00%
Bronze	Copper 80.0%; Tin 10.00%; Lead 10.00%
Commercial Brass (Regular)	Copper 61.5%; Zinc 35.5%; Lead 3%
Ketos Steel	Carbon 0.90%; Manganese 1.25%; Tungsten 0.50%; Chromium 0.50%
Steel (1020)	------------------
Babbitt	Lead 77.50%; Tin 10.00%; Antimony 12.00%; Copper 0.50%
Magnesium	Aluminum 2.5-3.5%; Manganese 0.20 min; Zinc 0.7-1.3%; Si .3 max; Cu. .05% max. Ni. .005% max; Fe .005% max. other elements .3 max - Remainder % Mg
Steel (4140)	Carbon 0.36%; Manganese 0.95%; Phos. 0.017%; Sul 0.021%; Ni 0.19%; Cr 0.99%; Mo 0.20%

Table IV

Dents and Measured Detonation Velocities for Small PETN Charges Confined in Various Materials, and for Various Wall Thicknesses

O.D.(in.) x10³(in.)	Magnesium Case *ρ = 1.37 (gm/cc) D = 6710 (m/sec) Dent x10³(in.)	Brass Case ρ = 1.35 gm/cc D = 6720 (m/sec) Dent x10³(in.)	Steel Case ρ = 1.35 gm/cc D = 6760 (m/sec) Dent x10³(in.)	Aluminum Case ρ = 1.42 gm/cc D = 7025 (m/sec) Dent x10³(in.)	Babbitt Case ρ = 1.34 gm/cc D = 6650 (m/sec) Dent x10³(in.)
1.00	13	36	36	18	28
0.90	13	36	36	20	
0.80	12	36	35	22	
0.70	12	34	36	22	29
0.60	13	35	36	19	
0.50	14	36	35	21	26
0.45				23	
0.40	16	35	35	24	30
0.375				25	30
0.350	16	34	33	25	28
0.325		34	31	24	29
0.300	16	31	30	23	28
0.275					29
0.250	16	27	29	24	26
0.225	16	38	29	19	
0.200	14	25	24	22	23
0.175	15	21	22	19	
0.160	15	17	19	16	

*ρ is the average density of the PETN charges.
 D is the average detonation velocity.

Table V

Dent and Detonation Velocity Measurements for Small Confined TNT Charges for Various Confining Materials and Various Wall Thicknesses

BRASS O.D.	ρ_s	D_e	d	STEEL O.D.	ρ_e	L_e	d	ALUMINUM O.D.	ρ_e	L_e	d	BABBITT O.D.	ρ_e	D_e	d
1.0	1.36	5582	29	1.0	1.36	5732	30	2.00	1.40	5670	24	1.0	1.45	5465	24
0.9	1.37	5524	29	0.9	1.36	5707	30	1.75	1.40	5674	14	.9	1.36	4740	24
0.8	1.36	5585	30	0.8	1.38	5750	31	1.50	1.44	5676	13	.7	1.39	4870	25
0.7	1.37	5534	28	0.7	1.27	5682	32	1.25	1.45	5665	13	.7	1.40	4930	24
0.6	1.36	5520	29	0.6	1.36	5650	30	1.00	1.37	5657	14.5	.7	1.33	4810	24
0.5	1.37	5618	30	0.5	1.37	5708	31	0.90	1.41	5626	15	.6	1.39	4985	25
0.40	1.37	5554	30	0.4	1.37	5613	29	0.80	1.42	5615	16	.5	1.39	4860	20
0.35	1.38	5552	29	0.35	1.36	5474	28	0.70	1.42	5714	17	.450	1.39	4800	25
0.325	1.35	5619	30	0.325	1.38	5474	26	0.50	--	--	--	.400	1.38	4950	22
0.3	1.36	5505	27	0.3	1.37	5501	24	0.50	1.42	5808	19	.375	1.36	4220	25
0.25	1.36	5637	25	0.25	1.36	5501	24	0.40	1.41	--	--	.350	1.35	4880	22
0.225	1.36	5522	24	0.225	1.37	5523	25	0.350	1.42	5682	18	.325	1.36	4740	25
0.2	1.36	5552	22	0.2	1.26	5404	22	0.325	1.43	5726	18	.300	1.36	5085	24
0.175	1.36	5464	19	0.175	failed	--	--	0.300	1.42	5744	18	.275	1.38	5190	22
0.165	1.37	failed	--	0.165	--	--	--	0.250	1.42	5757	16	.250	1.40	5204	21
0.160	1.36	failed	--	0.150	failed	--	--	0.225	1.43	5590	17	.200	1.40	5285	20
								0.200	1.42	5535	15	**	--	--	--
								0.175	1.43	failed	--	--	--	--	--
								0.165	--	--	--	--	--	--	--
								0.160	1.43	failed	--	--	--	--	--

*The column diameter was .150 inches. **Unable to load smaller diameter pieces.

O.D. - Outside diameter. d - case in inches - ρ_e loading density of explosive in gm/cc - D_e detonation velocity of explosive meters/sec - d depth of dent in thousandths of an inch

Table VI

The Depths of the Dents Produced in Steel by Various Diameter Tetryl Charges Showing the Effect of Confinement

Diameter of Column	Wall Thickness (inches)	Dents Produced by Tetryl Confined in Brass	Bakelite	Air
0.2	0.4	50	19	23
0.3	0.35	73	30	41
0.4	0.3	93	40	52
0.5	0.25	114	53	71
0.6	0.2	138	70	85

Density - 1.6 gm/cc
Column length - 0.75 inches
Dents are measured in thousandths of inches

References

(1) The Stability of Detonation, H. Eyring, R.E. Powell, G.H. Duffey and R.H. Parlin, Chemical Reviews, Vol. 45 pp 69-181

(2) The Detonation Velocity of Solid Explosives Contained in Long Cylindrical Tubes of Varying Weight, AC 1168, 6 September 1941, H. Jones

(3) Note on the Lateral Expansion Behind a Detonation Wave, AC 2093, 16 May 1942, G.I. Taylor, H. Jones

(4) Analysis of the Explosion of a Long Cylindrical Bomb Detonated at One End, RC 193, G.I. Taylor

(5) NAVORD Report 2202, Small Scale Technique for Measurement of Detonation Velocities, 27 December 1951, L. Hampton, R. Stresau

(6) NOLM 10381, Miscellaneous Physical Testing of Explosives, T.C. Smith, S.R. Walton, 1949

(7) OSRD 5746, Physical Testing of Explosives, L.C. Smith, E.H. Eyster, 1945

(8) NOLM 10765, Density of a Pressed Explosive as a Function of Loading Pressure, L. Hampton

(9) NAVORD Report 2137, Recent Developments in the Vacuum Thermocouple Timer, R. Stresau, C. Goode

(10) OSRD 5611 The Rate of Detonation of Various Explosive Compounds and Mixtures, Part II, M.D. Hurwitz

(11) NAVORD Report 90-46, Theory of the Detonation Process p 90, R.J. Finkelstein, G. Gamow

(12) AC 1168, RC 247 - Phys. Ex. 150, H. Jones

(13) J. Appl. Phys. 2444 (1953) R.C. Streffler, W.E. Deal

(14) Phy. Rev. 75 (1522) 1949, D.S. Hughes, W.L. Poudrom, R.I. Mimes

(15) J. Appl. Phys., Vol. 25 (1954) No. 10, J. Savitt, R. Stresau, L.E. Starr

(16) Proceedings of the Physical Society, Vol. 60, 1 January 1948, D.C. Pack, W.M. Evans, H.J. James

(17)   NAVORD Report 2864, The Propagation of Shock Wave in Aluminum, 28 April 1953, H. Dean Mallory

(18)   NAVORD Report 3753, Some Observations of the Onset of Detonation, J. Savitt

(19)   NOLM 8696, A Method for the Fabrication of Low M Electric Initiators, R.H. Stresau

(20)   NAVORD Report 2422, Small Scale Plate Dent Test Confined Charges, W.M. Slie, R.H. Stresau, 25 A

(21)   NAVORD Report 84-46, Detonation Time and Length Reaction Zone, G. Herzberg, C.B. Walker

Page numbers preceded by C refer to
Other numbers refer to pages in the